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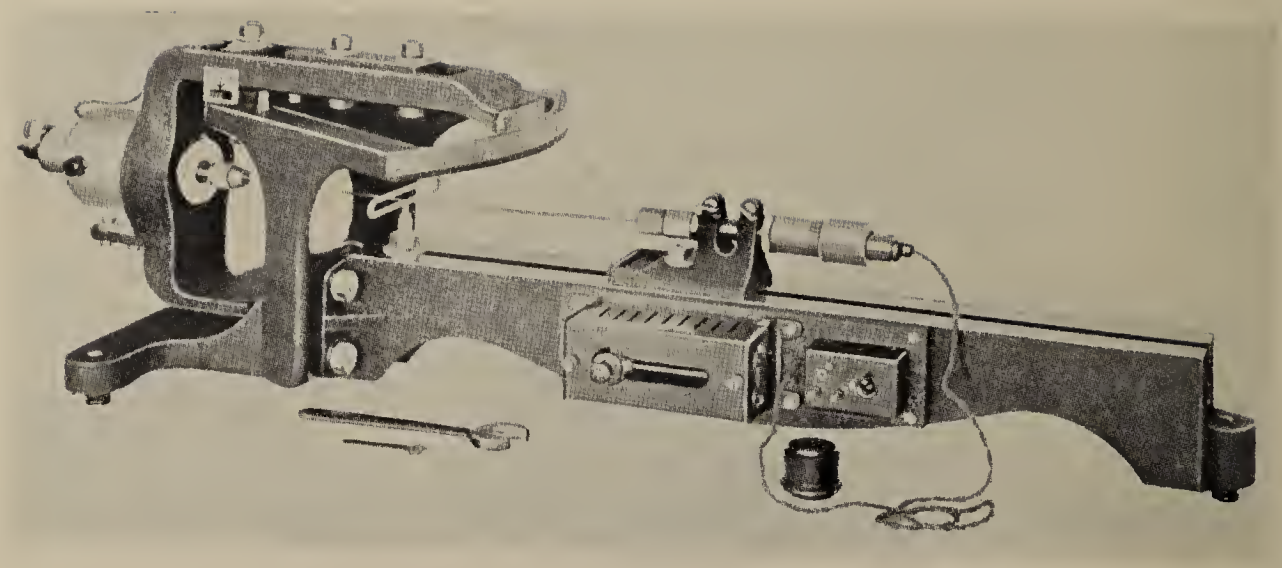
WIRE-DRAWING AND THE COLD WORKING OF STEEL



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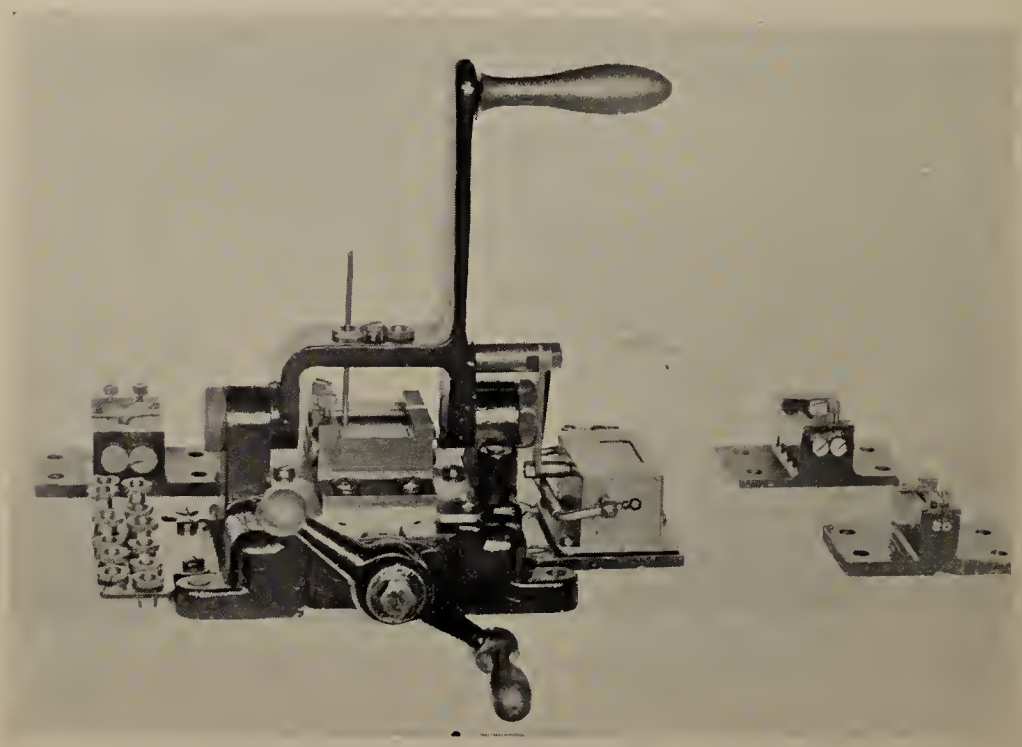

Frontispiece.

B

A. HAIGH-ROBERTSON WIRE FATIGUE TESTING MACHINE. Manufactured by Messrs. Bruntons (Musselburgh) Ltd.

B. BRUNTONS' WIRE BEND TESTING MACHINE

WIRE-DRAWING

AND THE

COLD WORKING OF STEEL

By

ALASTAIR THOMAS ADAM

Associate Royal Technical College, Glasgow

SECOND EDITION

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PREFACE TO THE SECOND EDITION

The main scheme of the original edition has been retained.

The intention has been to present the subject in such a way as will be of interest, not so much to the wire manufacturer as to the wire user.

The book has been curtailed slightly by the omission of four chapters. One dealing with Cold Rolled Strip and one with the Theories of Plastic Flow have been eliminated entirely, while the more important parts of the other two have been incorporated in the remaining chapters, and an additional chapter dealing with the Typical Application of Wire has been introduced.

The Author is greatly indebted to Dr Ferguson, of Messrs Colvilles, Ltd., for valuable assistance with Chapter II., dealing with the raw material.

He also wishes to express his thanks to Dr Goodacre and to Mr E. T. Gill for valuable assistance rendered.

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A. T. ADAM.

FEB 2 1955

PREFACE

SINCE the publication, in 1891, of *Wire : Its Manufacture and Uses*, by J. Bucknall Smith, no text-book dealing exclusively with wire and allied products of cold-working processes has appeared. All the more recent information on the subject lies scattered throughout the numerous technical publications with which the industrial world is now inundated.

The present volume is not an exhaustive treatise on the subject, but simply an attempt to explain the real nature of wire and other cold-worked products, to describe their physical properties, and to show how these depend on the treatment the material has received. The book is intended for the metallurgist, the engineer, and all those in general who are interested more in the product than in the process of manufacture. In describing the manufacturing operations the aim has been to emphasise those points which bear more closely on the quality of the products rather than to dwell unduly on those which are of importance from the commercial and productive point of view. Thus machinery and plant have been dealt with briefly, while such matters as the quality and preliminary treatment of the material, the extent of reduction by cold work, and the relation of these matters to the properties of the finished product have been discussed more fully.

The Author wishes to express his indebtedness to his Editor, Professor Thompson, for valuable help and advice, particularly in regard to Chapter IX.; to Mr Elvidge of Messrs Bruntons for the description of cold rolling in Chapter IV.; to the management of Messrs Bruntons for permitting him to publish the results of investigations carried out at their works; and to Mr Sinclair, the works manager, for kindly reading the proofs.

He also wishes to thank Mr G. C. Lloyd of the Iron and Steel Institute for permission to reproduce illustrations from their journals; Messrs Saville and Messrs Crossley for the loan of photographs of machinery; and others whose illustrations have been used with acknowledgment in the text.

A. T. A.

BRUNTONS' RESEARCH LABORATORY,
MUSSELBURGH, SCOTLAND.
April 1925.

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CHAPTER I

INTRODUCTORY

It is reasonable to suppose that the property which the common metals possess of being formed and worked at the ordinary temperatures would be discovered almost at the same time as the metals themselves. There is indeed abundant evidence to show that the cold-working operation is of great antiquity. Thus, it it is recorded in the Scriptures (Exodus, Chap. xxxix) that gold threads were made by beating the metal into thin plates and cutting them into wire.

Once the cold working had been applied to metals—almost certainly in the first place this would be accomplished by hammering—it would be quickly realised that this not only brought about a change in the shape of the metal, but also resulted in a hardening of the material. It is quite possible that this property of work hardening was more fully appreciated by the ancients than it is to-day. Long before the discovery of steel, work hardening was an important factor in the production of metal implements, and even steel weapons in those days owed some of their properties to the indirect effects of cold working, as instanced by the history of the Damascus blade. In this connection it is of interest to note that one of the most modern methods of obtaining a super-hardened steel—viz. the "*cloudburst*" method of Herbert[1]—is a work-hardening process.

The origin of wire-drawing itself is lost in antiquity. For many years one Rudolf of Nuremberg has been credited with the distinction of being the first man to draw wire through a die. Recent research in this direction, however, indicates that this claim is invalid and that the process was known long before Rudolf's time. The records of the city of Paris show that there were wire-drawing establishments paying taxes and observing a set of regulations governing working conditions before this, and quite recently a Latin MS. was found which proves that from 300 to 500 years before the Paris record wire-drawing was practised in its present form, and wire-drawing dies were commonly found in all well-equipped metal working shops.

Somewhere about A.D. 700–1000—the exact date is unknown—there lived a monk called Theophilus. This monk, who was either German or Saxon, seems to have devoted his life to the art of church decoration, and most of his writings deal with this subject. Among these are books dealing with the art of painting in oils, the fabrication of glass and stained-glass windows, and metal working. It is in this last work that a reference—the earliest so far discovered—to the wire-drawers die is found. Translated it runs as follows: "Two pieces of iron, three or four

fingers wide, smaller at the top and bottom, rather thin, pierced with three or four rows of holes through which wire may be drawn." Another reference runs as follows: "Mix two parts of tin with one of lead, hammer out the ingot long and slender and draw it through the holes of the wire-drawing plate." Other references in the works of Theophilus indicate that wire-drawing at that early date was an art sufficiently well known to require no particular explanation.

Metals may be altered in shape and size either by hot or cold working; the cold-working processes being used only because hot working is inconvenient or impossible. The true line of demarcation between hot and cold working is the recrystallising or annealing temperature of the metal. Above this temperature we have thermal equilibrium, and the mechanical deformation of the structure due to working is rapidly obliterated by spontaneous annealing. Below this temperature the crystals are permanently deformed by work. Any work carried out below the temperature of thermal equilibrium is in the strict sense cold work, although actually the metal may be quite hot. Thus a piece of iron hammered while at a temperature of 400° C. would be cold worked, but a piece of copper hammered at the same temperature would be hot worked, the annealing temperature of iron being about 520° C., that of copper about 250° C. Steel, and possibly some of the modern light alloys, may be cold worked at temperatures above the annealing temperature of the primary constituent. Above 520° C. ferrite is recrystallised but pearlite remains distorted. Thus the globularising of cementite, which occurred in the production of Damascus steel, may truly be regarded as a semi-cold working effect. In normal practice the distinction between hot and cold working is as a rule sufficiently obvious to avoid confusion, most operations which are usually classified as cold working being conducted at the normal atmospheric temperature, while hot working in the case of steel at all events is carried out at red heat.

That soft metals such as lead, copper, bronze, silver, and gold can be hammered or beaten without the application of heat must now be known to everyone, but few realise the extent to which cold-working processes are utilised in the production of familiar steel articles. Not only can metals be moulded to an extraordinary degree by hammering, rolling, and drawing, but they can actually be made to flow through an orifice by pressure, and rods and tubes of such plastic metals as lead and zinc are made to-day by this method of extrusion. Among the many forms of cold working are: punching, stamping, pressing, tube-drawing, rolling, hammering, swaging, and wire-drawing. To catalogue all the products of these various cold-working processes would be a difficult and tedious task, but some idea of the importance of the subject will be obtained by mentioning a few of the more important applications. Familiar articles made from cold-rolled steel strip are safety-pin caps, pen nibs, cycle rims, metallic hose, hinges, cartridge clips, etc. Bars of round, square, and hexagon, as well as of irregular cross-sections, are made by cold drawing for shafting, bolts, nuts, turbine-blading, pinions, etc. Enormous quantities of wire are used annually in making pins, needles, nails, fencing, links, hooks, surgical and dental instruments, springs, drills, taps, etc. A large percentage of the world's

output of copper is drawn into wire for electrical conductors, and in the manufacture of steel ropes we have probably one of the most important applications of cold-drawn wire.

The primary object of all these processes is that of forming the metal into a definite shape. In order that it may successfully undergo such operations the metal must possess the properties of malleability and ductility. It is important to note here that these two properties are not identical. Some of the very malleable metals are not at all ductile, at least in the practical sense—*e.g.* lead. The capacity of plastic flow in some metals is so great that they appear to behave more like highly viscous fluids than solids. On the other hand, the ductile metals—such as platinum, silver, iron, steel, copper, aluminium, and gold—which are suitable for drawing into wire, possess in addition to plasticity considerable tenacity. In considering this matter of ductility and malleability, however, it must be remembered that the difference is purely relative to the temperature and rate of traction, and that, considered from a wider and more scientific point of view, each metal may be malleable or ductile according to the temperature at which and the manner in which it is treated. Since we are restricted in practical cold-working operations to the ordinary atmospheric temperature, we must consider the metals from this point of view. By means of these properties we are able to mould metals without using heat into almost any shape or size with a degree of accuracy which equals that of any other process.

It has already been indicated that the cold-working operation accomplishes two things; the material is altered in shape, form, or size, and it is work hardened. Owing to the latter factor the cold working of metals cannot be carried on indefinitely, because every blow of the hammer, every pass through the rolls or drawing die decreases the ductility and increases the hardness of the metal, until a point is reached at which it becomes so brittle that it will stand no more punishment without breaking down. Before this point is reached the metal must be "annealed" —*i.e.* heated to a certain temperature to restore its ductility—after which the cold-working process may be continued. In such a way, by cold working alternated with annealing, gold, the most malleable and ductile of metals, can be reduced to a leaf thin enough to transmit light; while one grain of gold has been drawn into wire 500 feet in length, and platinum wire as fine as 0·00003 inch diameter has been produced for spider lines in telescopes by encasing it in silver, which was afterwards dissolved. Steel, a much harder metal, can be reduced to the dimensions of a human hair.

If the sole object of cold-working processes were to alter the shape and size of the metal, the loss of ductility might be regarded as a serious drawback to such methods of shaping metals. In many instances it is so, but in other cases the increase in tenacity which accompanies the loss of ductility is desired; and, although this modification of the physical properties is usually a secondary object, it is sometimes of an importance equal to that of the actual production of such an article as a wire, and occasionally becomes the primary object. This affords a convenient

basis for the classification of cold-working processes, permitting the products to be placed into two broad groups:

(1) Where the object of shaping the material accurately to the desired form is the only one; and where the hardening effect of cold work is not desired, and has to be removed at various stages or at the end of the operation by annealing.

(2) Where the object is not only to shape the material, but also to harden and strengthen it, and where the final annealing is omitted.

As is usual when such rough classifications are made, there is no hard and fast line between the two. Thus, in some instances, the hardening effect of cold work, although it is utilised in the finished product, is of such slight importance that it is difficult to say into which class the material should be put, and there is some difference of opinion in certain cases regarding the desirability of utilising the modification of the physical properties. On the whole, however, the classification will be found useful. For example, thick bars of mild steel for shafting and for use in automatic lathes are now frequently cold drawn, because this is the best method of obtaining a bar of suitable shape and of the correct size with a smooth finish. Although the reduction in diameter in such bars is very slight—viz. from $\frac{1}{32}$ to $\frac{1}{8}$ inch—it is nevertheless sufficient to alter the physical properties of the steel to some extent, an incidental effect which is not usually desired, and which, in the opinion of some, is objectionable. In other articles also made of steel and non-ferrous metals, which are finished by a cold-working process, the hardening effects of cold work are allowed to remain not so much because they are desired as because it is not considered necessary to remove them by annealing. Such products naturally fall under Class I. In others, again, a slight hardening of the metal beyond the normal hardness is desired, but this effect is of minor importance, and these products also are more conveniently placed in Class I. In Class II. we wish to place only material in which the hardening effect of cold work is of, at least, equal importance to the reduction in size.

The ordinary conception of a wire is indicated by the French name for it—in English "a thread of metal." It is regarded mainly as material of certain dimensions. The English word "wire" (A.S. *wīr*) carries a suggestion of its physical properties. One uses the word "wiry" to denote something which possesses great strength, together with flexibility; the strength of the sapling as opposed to that of the rigid oak. Steel wire is a structural material possessing peculiar properties. From the metallurgical point of view it is not to be regarded so much as a fine thread of metal, but as steel with its normal properties greatly enhanced by cold work. One is so apt to look upon the wire-drawing process merely as a means to one end, that the very important effect of the plastic flow on the properties of specially heat-treated steel receives less attention. The development of aircraft, involving the extensive use of structural members of cold-drawn wire, has lately focused attention on the extraordinary properties that can be obtained in ordinary carbon steel by

intelligent cold working, and an interest in the subject has been aroused among those out of direct touch with the cold-working trades. More recently further attention has been attracted to the possibilities of cold-drawn wire as a structural member by its use in the form of wire ropes in H.M. Airship R100, and by the failure in the United States of an attempt to substitute heat treated—*i.e.* oil quenched and tempered—for hard-drawn wires in suspension-bridge building.

Reference

[1] "The Work-Hardening of Steel by Abrasion," by E. G. Herbert. *Journal of the Iron and Steel Institute*, 1927, No. 2, p. 277.

CHAPTER II

RAW MATERIAL AND ITS PREPARATION

ALMOST every stage in the history of the wire from the ore onwards is of importance from the point of view of the finished product. Here it is necessary to omit any consideration of the earlier stages and to take the steel ingot as the starting-point. Probably no single factor contributes more to the satisfactory production of a high-grade steel wire than the quality of the steel. The importance of extreme purity in promoting easy flow in ductile metals has been fully demonstrated, though it is not always clear what forms of impurity are most objectionable.

Steel specifications lay down the minimum and maximum percentages of the desired elements together with a maximum value for such impurities as sulphur, phosphorus, silicon, etc. Occasionally one may find a vague reference to non-metallic inclusions, but more frequently the absence of all other harmful impurities is supposed to be guaranteed by that delightful clause, "The material shall be free from defects." Certainly if this were to be taken literally, and assuming we could readily be supplied with material "free from defects," there would be no need for the wire manufacturer to consider the matter further. But what are defects? To the wire-drawer obviously anything which interferes with wire-drawing, with ductility, and with easy flow is a defect. Until the mechanism of cold flow in metals is completely understood the exact part played by impurities cannot be perfectly clear. Sufficient, however, is known about this matter from actual experience to enable us to state that the more closely a ductile metal or alloy approaches perfect purity the more cold work it will stand without breaking down, *provided the flow is uniform throughout the metal.* For example, gold is a metal which is readily obtainable in a relatively pure state, and it is the most ductile of metals. Certain alloys of nickel and iron have recently been made in a very pure state in the induction furnace and have proved extraordinarily ductile. It has been found possible in one case to reduce a wire of such an alloy from 0·160 inch diameter to 0·008 inch diameter without intermediate annealing. Not every kind of impurity interferes with cold flow. As a general rule impurities existing in solid solution appear to have little or no harmful effect; it is only when these are precipitated from solution in a finely divided state that they begin to interfere with the normal flow of the metal.

Perhaps the effect of non-metallic particles may best be visualised by considering that of carbon as an impurity in iron. Fortunately the condition and distribution of this element can be controlled by heat-treatment, but since carbon can have a deleterious effect something may be learned regarding the probable

Plate I.

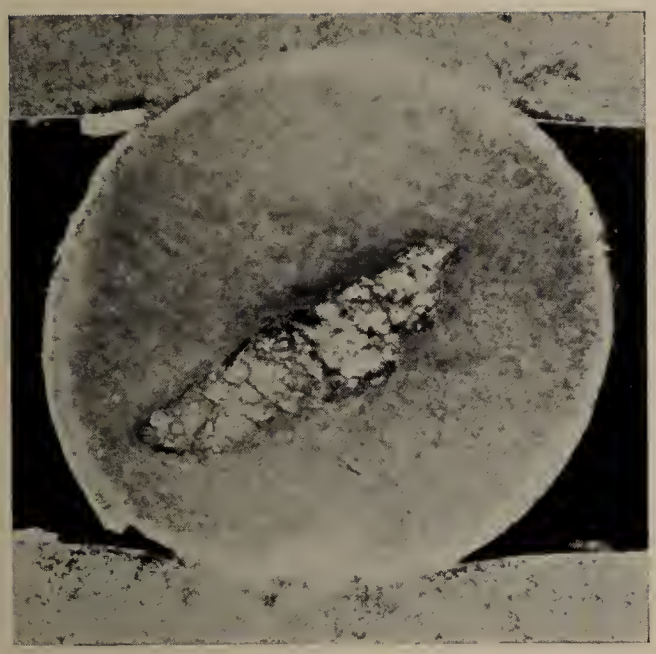

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Fig. 1. CROSS SECTION OF WIRE DRAWN WITH PIECE OF RUNNER BRICK INSIDE. Magnified 20 Diameters

Fig. 2. LONGITUDINAL SECTION OF WIRE SHOWING DISTURBING EFFECT OF MINUTE INCLUSION. Magnified 50 Diameters

Fig. 3. TYPICAL "CUPPY" FRACTURE IN WIRE DUE TO SEGREGATION. Magnified 50 Diameters

behaviour of other impurities from a study of the influence of this element on iron. Above 900° C. carbon exists in all steels in solid solution with the iron forming the metallographic constituent austenite, which is known to be moderately soft and very ductile, indicating that carbon in solid solution does not seriously impair the cold-flowing properties of iron. On cooling, iron carbide (cementite) is precipitated from this solution, and the steel is then composed of two primary constituents—viz. soft ductile iron (ferrite) and very hard iron carbide. The hardness of the steel depends mainly on two things: the amount of iron carbide present, and, its distribution and state of division. This latter point is mainly determined by the rate of cooling. Under certain heating and cooling conditions the constituent troostite is formed in which the iron carbide is so finely divided and exists in such minute particles that whole mass of metal is hardened. When the hardened steel is tempered by heating above 500° C., the sub-microscopic particles of carbide coalesce into granules large enough to be visible under the highest powers of the microscope, producing the constituent sorbite, which is sufficiently ductile to stand cold flow. *Thus the microscopically visible particles of the very hard carbide do not seriously inhibit cold flow, while the innumerable sub-microscopic particles do.* Somewhat similar appears to be the behaviour of solid non-metallic inclusions in steel. Inclusions of relatively large magnitude may sometimes be found in wires, and no serious interference with the flow of the steel seems to have resulted from their presence. No difficulty, for example, is experienced in drawing free-cutting steel into wire, in spite of the presence of manganese sulphide inclusions, and many tons of wrought iron containing slag have been drawn into wire. The case of a wire drawn from 5 to 13 gauge, with a piece of runner-brick inside, may also be cited (Fig. 1). Apparently such relatively massive bodies of non-metallic material may occasionally be carried along by the general flow of the ductile metal, while smaller particles, by interfering with the flow at a particular point, cause internal rupture, which spreads. A minute inclusion may cause a disturbance of the structure out of all proportion to its size, as may be seen from Fig. 2. This disturbance is due to an inclusion which is quite visible under the microscope; what we cannot readily determine is the effect of invisible impurities on the ductility of the metal. Atkins [1] refers to oxygen, meaning, of course, oxygen in combination, as "one of the greatest enemies of the wire-drawer, as it is the principal cause of "running out"—*i.e.* enlarging of the die while a piece of wire is being drawn so that the diameter of the back end of the coil is larger than that of the front or "point" end. He attributes this to the effect of minute oxide specks present in vast numbers—about 150,000 to the square inch of surface—acting as a very fine abrasive.

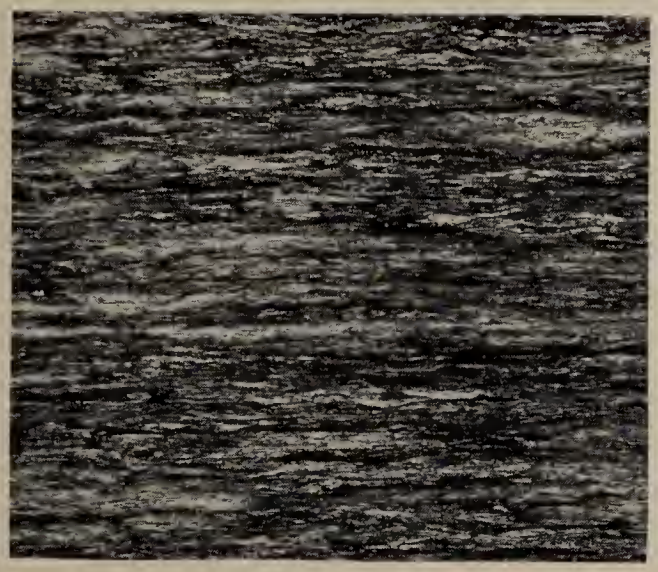
This experience has been confirmed by others, particularly in the case of Al_2O_3 or Alumina, and for this reason the use of aluminium as a deoxidiser for wire steel is now frequently avoided and sometimes expressly forbidden. But the action of hard oxide particles as a grinding agent on the bearing of the die is not the only, nor probably the most important, part played by oxide as an enemy of the wire-drawer. Oxide particles, or non-metallic inclusions containing oxygen, interfere

with the regular flow of the individual crystals. In bad cases this effect can be seen in wire with a wavy fibre, as illustrated in Fig. 4. Moreover, certain steels cannot be drawn "level-ended"—*i.e.* of the same diameter from end to end—even when the grinding action on the bearing of the die is eliminated by covering the wire completely with a coating of some softer metal such as copper or zinc. Nor is it only visible oxide particles which interfere with the flow of the steel in this way. Occasionally a steel is found unsuitable for wire-drawing, owing to its reluctance to "sink" in passing through the die, and such steel is often apparently free from oxide particles when examined microscopically. It is known that, like carbon, iron oxide is more soluble in iron in the γ than in the α condition, and as the steel is cooled some of the oxide is precipitated in an emulsified form—a condition analogous to that of the carbon in troostite—and in this state it is possibly more dangerous than in that of visible and larger particles. It is naturally difficult to get any direct evidence of this, and it is an hypothesis founded purely on conjecture.

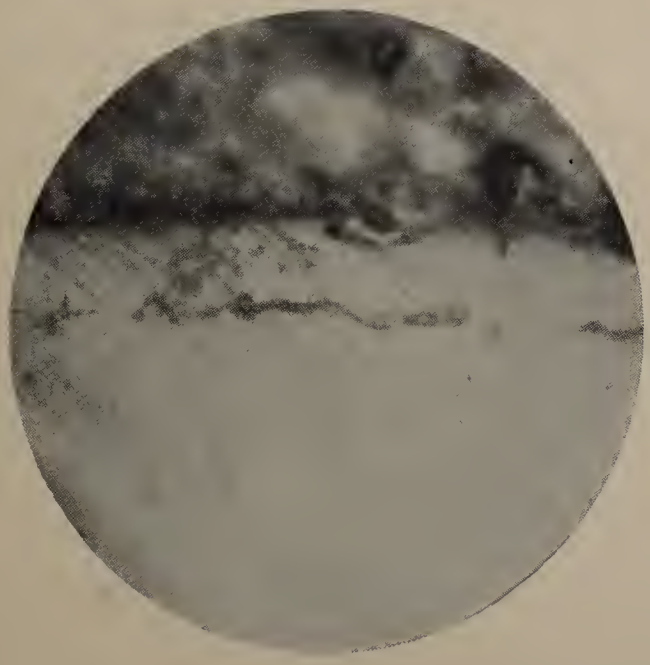
In the past acid steels and particularly some of the best brands of acid steels, made from pure Swedish ores, have been thought by the wire manufacturer definitely to make better wire than basic steels. This would seem to substantiate the above remarks, in that acid steels from the mode of manufacture are presumably freer from combined oxygen than basic steels. Experience in steel-making practice has shown that in order to minimise oxidation in the bath and to ensure that all the reactions take place quickly and efficiently, refining must be carried out at a high temperature; also, that pouring must take place at as low a temperature as possible, in order to prevent the ingot from cracking, and to ensure minimum grain size. A "pure" steel—purity being gauged by freedom from the oxidation products of its deoxidisers, viz. SiO_2, Al_2O_3, MnO, Cr_2O_3, or slag such as the silicates $2MnO \cdot SiO_2$ or $2FeO \cdot SiO_2$, etc.—will withstand a maximum degree of undercooling without premature solidification. This is on account of its relative freedom from nuclei which initiate crystallisation. The degree of deoxidation, degasification, and slag removal is really the steel purity which determines its capacity for undercooling even below its theoretical melting-point without crystallisation. These factors obtain with steel-making in general, and not with any particular process, and are the outcome of the last 20 or 30 years experience, so that it becomes increasingly clearer that the quality of the steel produced depends principally on the control of the melting and casting conditions, and to a much less degree on the actual process used—*i.e.* whether acid or basic.

One extremely simple test may be mentioned here which has been found very useful, when used with discretion by an experienced man, as a guide to the quality of a steel for wire manufacture. This is the boiling-acid test. It is a test which is well known for detecting pipe and segregation in steel billets or bars, and for surface defects in wire rods, but its value as a general test of the purity of the steel internally as well as superficially is probably not appreciated. The rod is boiled in hydrochloric acid, either 50/50 strength or concentrated, for 5 to 10 minutes, and then

Plate II.



4



5

Fig. 4. LONGITUDINAL SECTION OF WIRE WITH WAVY FIBRE DUE TO INTERFERING EFFECT OF INCLUSIONS.
Magnified 150 Diameters

Fig. 5. SCALE EMBEDDED BELOW THE SURFACE OF A WIRE

washed and freed from any adhering scum, when its quality may be judged by its appearance and the uniformity of the acid attack.

It may seem that this apparently crude test could not be expected to reveal anything regarding the general purity of the steel, but it is the author's experience that those steels which show up best under this test usually make the best wire. Possibly the explanation is that uniformity in acid attack is an indication of homogeneity, and indirectly an indication of comparative freedom from solid non-metallic inclusions. All types of defects are not, of course, revealed by this test, but one example may be given to illustrate its extreme delicacy in certain instances. A steel which had developed a fine seam or crack in service was carefully examined microscopically in the neighbourhood of the flaw without any cause being detected. The same microsection was then subjected to the boiling-acid test with the result that two fine streaks were immediately revealed. Subsequent re-etching of the section with Stead's reagent showed the presence of two fine ghost lines in the same position.

Before leaving this test it may be well to mention the type of defect it was originally introduced to detect in wire rods—viz. surface defects such as laps, cracks, seams, reeds, etc. Every manufacturer of cold-worked material knows only too well the heart-breaking troubles which arise through such defects in the wire rod or billet. In cases where the wire has to have a bright or polished finish any such defects, of course, condemn the rod immediately, but even in rope wire where the defect may be hidden from view, it will be immediately revealed under the torsion test. It is, perhaps, not generally realised even among wire manufacturers how sensitive is the torsion test to slight surface defects on the wire. Even a die mark may cause a concentration of stress in the skin in its neighbourhood and reduce the number of twists by 2 or 3, thereby causing rejection of the wire.

It is hardly necessary here to enlarge on what are probably the most serious types of defect in wire steel—viz. pipe and segregation—since it is now fully realised that axial segregation must be eliminated by efficient cropping of the ingot in wire steels. Such segregation inevitably leads to irregular flow through the drawing die and ultimately to "cuppy" wire. Perfect freedom from segregation is, of course, impossible, and no ingot is completely homogeneous, however carefully the steel is made or cast. The other elements and their compounds which are present in solution in the liquid iron distribute themselves on solidification, according to well-known laws of selective freezing. Wire steel, however, can and should be cast in small ingots where the segregation can be confined almost entirely to the feeder head and the top portion, which can be readily cropped off, so that when the remainder of the ingot has been rolled into a coil of rod it is reasonably similar in composition from end to end.

Fig. 3 illustrates a typical "cuppy" fracture caused by axial segregation.

Minor segregates also occur in other portions of the ingot, notably at the boundaries of the columnar and the equiaxial crystals. These generally result in the formation of ghost lines containing inclusions of oxides, manganese silicates, and

manganese sulphide, and although less serious from the wire-drawing point of view than axial segregation, their presence is nevertheless objectionable in steel which is to be used for the production of high-grade wire. In the manufacture of ordinary soft steels for wire, deoxidation can be carried out sufficiently far to minimise piping and yet not so far as to give rise to "blowing." This so-called "half and between range" is quite wide with soft steel, but in the case of high carbon steels there is no intermediate stage so that the same method cannot be adopted in this case.

The most essential points to be observed in the making of a good quality steel may be summarised as follows:

(1) The materials used must be as pure as possible and not contaminated with such elements as chromium. This precludes the use of a hearth on which alloy charges have been recently made unless it has been very thoroughly cleaned and fettled.

(2) The bath contents should be very thoroughly melted and refined under controlled conditions.

(3) Deoxidising agents must be used with great care, and the ladle, moulds, etc., should be well cleaned so that the products of the former and the pick-up of impurities from the latter are kept down to a minimum. Otherwise, as already earlier stated, premature solidification due to the effect of these nuclei will take place with subsequent ill effects upon the quality and properties of the steel. The procedure given here, efficiently carried out, will allow casting at low temperatures with consequent benefit to the steel.

(4) The rate of pouring, in relation to the size of the ingot, should be predetermined so that crystallisation in the ingot will proceed satisfactorily and the product will be reasonably free from segregation.

In extreme cases, where exceptional purity is desired, it is sometimes necessary to sacrifice most of the upper half of the ingot and increase the discard considerably.

Before leaving this important question of the quality of wire steels, it may be well to conclude by considering the chemical composition of the steel and the effects of impurities and alloying elements. With regard to sulphur and phosphorus, it is not so much the amount of these elements present as their distribution that is important. The effect of their presence is to be considered together with the question of segregation. Thus a study of the macro- and microstructures, either by means of sulphur prints or special etching, is usually more instructive in determining how these elements are likely to affect the steel than chemical analysis. The degree of segregation is highest for carbon, phosphorus, and sulphur, but almost negligible for manganese and silicon. In general, segregation of carbon and phosphorus is intensified:

(1) As the carbon and phosphorus contents increase.
(2) As the rate of freezing falls.
(3) As the size of the ingot increases.

Sulphur, although it exists in the liquid steel in the form of minute globules of an immiscible complex sulphide, tends to collect in the same portions of the

ingot as the carbon and phosphorus. It should be added that high sulphur and phosphorus content often indicates that other possibly more objectionable impurities are also present—in making basic steel the sulphur content very often is a useful indication of the general conditions of the bath and the slag—so that it is sometimes necessary for the wire manufacturer to specify low limits for these elements.

For general purposes the limits for sulphur and phosphorus contents laid down in British Standards Institution Specifications are satisfactory.

Apart from these impurities known to be harmful, we have to consider how the presence of such elements as manganese, silicon, copper, and the special elements of the alloy steels affect steel for cold working. This must be dealt with from two points of view:

(1) The effect on cold working.
(2) The effect on the ultimate use of the product.

Taking the latter first, it is often necessary, in cases where a steel of special composition has to be reduced to certain dimensions by a cold-working process, to modify the usual procedure in order to suit the altered conditions. Of course, when the steel falls into the category of our first class of cold-worked material, the effect of composition on the cold-working operations must be a secondary consideration, and ways and means have to be found of applying cold work to steels which are often of a refractory nature—*e.g.* many of the alloy steels.

SILICON

It has been claimed by some that high silicon steel is good for wire manufacture. On the other hand, breakages in high carbon steel during heat-treatment, in pickling, in the early drawing stages and in galvanising, have been found on occasion to be associated with high silicon content. The truth is that silicon content as determined by ordinary analysis where no distinction is made between silicon and silicates means almost nothing unless one knows the conditions under which the charge was made. Silicon is undoubtedly one of the most useful and efficient deoxidisers. It gives a solid steel, reduces segregation and blowholes. It permits the use of a lower manganese content, which is often desirable. It obviates the temptation to use aluminium, which is objectionable in wire steel. It may happen, however, that a charge is over-oxidised in the bath by cold melting, over-feeding, etc., and an attempt is made to deoxidise it by a large ferro-silicon addition, either to the furnace or the ladle. This does harm because of the large amount of non-metallic impurities which result from the products of deoxidation. These will analyse as silicon instead of silicates, etc. Thus it is possible to have a good steel very high in silicon because it is silicon and not silicates. From the steel-making viewpoint a useful limit is 0·30 per cent., the figure specified as the maximum in B.S.I. specifications.

MANGANESE

Manganese, apart from its use as a deoxidiser and scavenger for sulphur, hardens the steel and increases its strength. Its influence increases with carbon content. Expressed quantitatively the rate of increase in the ultimate strength when the steel is in the normalised condition is roughly from 100 to 250 lbs. per square inch for each 0·01 per cent. of manganese, the higher figure being for the higher carbon steels. With 1 per cent. manganese the eutectoid composition of steel is reduced to about 0·78 per cent. carbon. Thus a greater hardening effect may be obtained with a carbon content of 0·65 to 0·70 per cent. and a manganese content of 1 per cent. than with a carbon five points higher and half the manganese content.

The real significance of manganese on wire steel, however, lies in its influence on the pearlite constituent, as illustrated in Figs. 42 and 44. It is true that the sorbitic structure of Fig. 44 can be obtained in a low manganese steel by more rapid cooling, but manganese when present to the extent of about 1 per cent. not only assists in the production of the fine variety of pearlite required in hypo-eutectoid steels, but even makes possible the use of hyper-eutectoid steels for high tensile wire. In steels containing up to 1 per cent. carbon it prevents the formation of the free cementite network which interferes with drawing in lower manganese steels and produces a very hard variety of pearlite or sorbite which is yet sufficiently ductile to be drawn with care. Wire of this type is preferred by some for spring making, but it is really doubtful if the slight increase in elastic properties so obtained is sufficient to warrant the sacrifice in toughness involved.

The question of the influence of manganese in wire steel is really part of the general one of how best to balance the factors of composition, heat treatment, and cold work in producing a desired result in the finished wire.

ALUMINIUM

is usually found in steel in the form of the hard oxide, and where present it tends to make the wire "run out"—that is, it grinds the hole in the draw-plate larger, and results in the back end of the piece of wire being larger in gauge than the front end. For this reason the use of aluminium as a deoxidiser in wire steels is undesirable. Unless present to excess it does not, as a rule, cause trouble in the larger sizes of wire, say under 18 gauge, but in the wire to be drawn over 22 gauge the use of aluminium should be prohibited. Actually there is no need for the use of aluminium as a deoxidiser in wire steels at all, but wire makers specifying high carbon steel and a manganese content of say 0·3 to 0·4 per cent. or less, with a silicon content of 0·05 to 0·15 per cent. leave the steel maker little option. Wire makers, as well as other steel users, will be well advised to avoid unnecessary restrictions in specifying. Much bad steel is the result of unnecessarily rigid specifications issued by people who do not understand steel making.

COPPER

"The Influence of Copper in Steel for Wire" forms the subject of a paper by Stead and Wigham,[2] and a study of their investigations leads to the conclusion that, apart from a slight improvement in resisting solubility in acid, copper has no beneficial, but often a deleterious effect; especially is this the case with high carbon steels, so that its presence in wire steel should be avoided. The results, however, certainly do not warrant the rejection of wire containing high copper, provided the wire has drawn satisfactorily and stood up to the required physical tests.

Quite recently there has been a revival of copper-bearing steels, and the author has had the opportunity of testing some of these in the form of wire and rope.

Copper-bearing steels, when properly made, do reduce quite definitely the solubility in weak acid solutions, a point of considerable importance in dealing with haulage ropes working in acid-bearing water. The presence of copper has also a distinct influence on the resistance to atmospheric corrosion, as has been demonstrated by the work of the Corrosion Committee of The Iron and Steel Institute. As the figures in Table 28 at the end of Chapter VI. show, the solubility of patented steel wire in 1 per cent. sulphuric acid may be represented by a loss in milligrams per square centimetre in 120 hours of well over 100, while that of a good copper-bearing steel wire has been found as low as 16.

NICKEL AND CHROMIUM

as accidental ingredients of steel are not beneficial in wire, as, like manganese, they upset the ordinary method of heat-treatment, making hard steel more sensitive in patenting, and in annealing offering considerable resistance to low temperature treatment.

To conclude this brief consideration of the effects of impurities on wire steel, the author's belief is that, when heat-treatment operations are carried out in the most efficient manner, the ideal for high-grade wire is a steel which most closely approaches the pure iron-carbon alloy. Only additions such as ferro-silicon, which are necessary for deoxidation, are desired.

THE WIRE ROD

The raw material of a wire mill consists of wire rods in coils, which are obtained from the steel ingot and billet respectively by hot rolling. A wire rod varies in diameter, in general, from a little under $\frac{1}{4}$ to $\frac{1}{2}$ inch, although wire rods in coil are now produced in sizes up to 1 inch diameter. The smallest size of rod produced by hot rolling is, as a rule, No. 5 S.W.G., or 0·212 inch diameter. Occasionally smaller rods are produced, but by far the largest tonnage of wire steel is rolled to No. 5 S.W.G.; below this it is not very practicable to go on hot rolling. Naturally,

the size of the rod selected to produce wire of a certain gauge is the smallest possible consistent with the production of a smooth round wire, and, in the case of high tensile wire, with due allowance for the requisite amount of cold work. For instance, for soft mild steel wire, where great tenacity is not required, all wire smaller than 8 S.W.G. would be drawn from a 5 S.W.G. rod, and, as a rule, a reduction of two to three gauges is required to make the hot-rolled material perfectly round; while in some cases, where maximum tenacity is required, it is necessary to allow for a reduction of about ten gauges.

In this country a coil of ordinary steel wire rod usually weighs about 120 lbs., but sometimes the coils weigh as much as 300 lbs., or as little as 10 lbs., the weight, of course, depending largely on the class of material and on the type of rolling mill. The diameter of the coil is generally about 30 inches. The wire rod should naturally be as nearly round as possible, free from cracks, flaws, spills, laps, reeds, etc. Such defects, although not always apparent in the rod as received, quickly reveal themselves in drawing. A rod that is badly off the round is apt to give considerable trouble in drawing, because of the irregular flow caused in rounding up. This sets up internal stresses which are difficult to remove by subsequent heat-treatment, and, according to Longmuir,[3] the wire is apt to develop a "fixed habit," irregularities in the properties of the hot rolled rod causing similar irregularities in the wire drawn from it. Another common source of trouble, due to lack of care, is overheating in the rod-rolling mill, frequently accompanied by slight burning and excessive decarburisation.

Rolling defects are responsible for many of the troubles with which the wire manufacturer has to contend. Among the more important of these are:

(1) Overheating and burning.
(2) Decarburisation.
(3) Overlapping.
(4) Spills, seams, fins, guide marks, and pitting caused by roughened roll grooves.
(5) Buried scale, due to too high rolling temperatures.

BURNING

Burning occurs chiefly in high carbon steels when they are heated to a temperature approaching the melting-point. The steel becomes red short as well as extremely brittle when cold, and breaks with a coarse fracture.

This excessive brittleness, it is generally agreed, is due to a weakening of the cohesion at the intercrystalline boundaries. Some attribute this to the evolution of gases, such as carbon monoxide, hydrogen and nitrogen, which, under the influence of high temperature, force the crystals apart. Others believe it is due to oxidation. The presence of oxides at the grain boundaries certainly does result in a typically brittle metal, and explains the impossibility of restoring burnt steel by forging, the oxide interfering with the welding of the crystals. The fact that steel is not burnt

when cooled in the ingot mould is explained by the evolution of reducing gases effectively preventing oxidation, and argues that the presence of oxygen is the chief factor which influences burning. Stead,[4] on the other hand, believed that the burning of steel was not due to the presence of oxidising gases, but to incipient fusion, due to the presence of envelopes rich in phosphorus; and Gutowsky has obtained results which, if correct, would make burning in certain steels possible at temperatures as low as 1150° C. Giolitti [5] also appears to hold the view that burning is due to the low fusion temperature of zones rich in impurities, and consequently that heat-treatment at temperatures just below this point will decrease the tendency of the steel to burn by allowing solid diffusion to take place.

For commercial steel the following temperatures are given by Brearley as danger limits:

Carbon, per cent. .	0·1	0·3	0·5	0·7	0·9	1·1
Temperature ° C. .	1460	1400	1330	1260	1200	1130

It seems probable that all these views are correct in a sense, and that the error lies in applying the term "burning" to anything which causes "a mechanical separation of the grains on extreme overheating."

DECARBURISATION

Slight decarburisation is inevitable in wire rods unless special precautions are taken to avoid it, such as heating the billets in a reducing atmosphere, but provided it is not excessive it is, perhaps, beneficial in providing a soft drawing skin in contact with the drawing die. For certain purposes, however, wire must be completely free from surface decarburisation. All high carbon tool steel wire, where surface hardening may be essential, must, therefore, be ground at some stage to remove the decarburised skin. It is also essential to remove decarburisation from all rod which are to be used for the manufacture of high-grade hard-drawn spring wire such as aero engine valve spring wire, where the springs are subjected to severe torsional fatigue stresses, and, in the latest Air Ministry specification for such wire, grinding of the rods has been made compulsory. Excessive decarburisation is, of course, to be avoided in all cases, since it causes irregular flow in drawing, and is one cause of "cuppy" wire.

OVERLAPPING

is a very serious fault, which should be strictly avoided in rolling rods for wire-drawing, and no rods should be passed into the wire mill without careful inspection for this and other surface defects. The author has found it pays to test at least 10 per cent. of every rod consignment for these faults, and 100 per cent. if any faulty coils are found in the first instance. Overlapping can generally be detected by the boiling-acid test described on page 20. This can be followed in doubtful cases by the up-ending or "dump" test, which consists in flattening out a cross-

section of the rod while at the forging temperature until it has increased in diameter to about twice the original. If laps are present, the up-ended section will burst at the edges. As a final test, microscopic examination may be necessary, and there it is almost invariably found that overlapping has occurred in two places on opposite sides of the cross-section of the rod.

SPILLS, SEAMS, FINS, AND GUIDE MARKS

Spills and fins can generally be seen by examining the rods in coil, but etching in boiling acid is necessary to reveal seams and guide marks. These faults are, of course, of a minor character, and rods need not be condemned because they are not entirely absent, unless very special wire is to be made. The degree to which they may be permitted is sometimes very difficult to decide, and one can judge only by experience in such matters.

BURIED SCALE

is not so easily detected. Hot rolling at a very high temperature often causes scale to be embedded in the rod to such an extent that it cannot be readily removed in the pickling tank and the wire pulls out the hole in the draw-plate (Fig. 5). The best remedy for this trouble is to allow a fresh, loose scale to form on the rod during heat-treatment, which breaks away the old scale and enables the rod to be properly cleaned. "Weathering"—*i.e.* allowing the rods to rust—also helps to loosen the surface, and when very dirty rods come into the cleaning house they are sometimes allowed to "dry rust" after leaving the pickle, and are recleaned the next day.

These minor surface defects, if not present to such an extent as to necessitate rejection of the material, make the preliminary cleaning or descaling of the rods a most important operation, since any dirt or scale which remains lodged in the steel is bound to cause trouble in drawing. Much of the trouble experienced with the non-sizing of wire which is attributed to faulty steel is in all probability often due to imperfect descaling in the initial pickling.

DESCALING OR PICKLING

Leaving aside for the present all heat-treatment operations, which will form the subject of a later chapter, the most important process in preparing the material for cold working is descaling or cleaning. The raw material as received from the hot-rolling mill is covered with scale or oxide, and this has to be removed completely. Many attempts have been made to descale metals by mechanical means entirely, but though this can be done readily enough with small metal parts or bars and straight rods, for various reasons such methods have not found successful application in dealing with wire rods in coil, with the result that there is only one efficient way of cleaning in bulk—viz. by pickling in acids. Pickling, however, can be greatly assisted by the use of banging machinery.

The acids used for steel are hydrochloric or "spirits of salt," sometimes called "muriatic" acid, and sulphuric acid or "vitriol." For other alloys suitable pickling agents are employed according to the metal.

For the following reasons rod pickling should differ somewhat from wire pickling:

(1) A thicker and more adhesive coating of scale has to be removed. The type of mill in which the wire rod has been hot rolled appears to influence the adherence of the scale, that on rod from a continuous mill being often much more firmly attached than that from mills of the looping type.

(2) The rod itself has a rougher surface, and the pickling action must penetrate deeper so as to ensure the complete removal of every particle of scale. Unless every attention is paid to this preliminary pickling operation there will be endless trouble in the subsequent process. Hard scale is sometimes embedded in the wire, and is not revealed until it has been drawn several passes—*e.g.* a very slight "fin" or "ridge" in a wire rod sometimes covers scale—which ultimately produces a scratch or groove in the wire—a frequent cause of failure in the torsion test. It is often stated by wire-drawers that rods cannot be drawn at all, unless all scale has been removed, but this is by no means true, as Fig. 5 demonstrates. Pockets of scale may be left on a rod and cause little or no trouble in the preliminary drawing owing to the fact that the scale is covered with the coating, lime and soap lubricant, and therefore does not come into contact with the bearing of the die. But it is drawn into the skin of the wire, and generally reveals itself in no uncertain manner at some later stage in the drawing operations. Complete removal of all scale is, therefore, essential when wire with a smooth round finish is required. Naturally, in dealing with very cheap grades of wire such as nail wire, the same care is unnecessary, but even here careful attention to the preliminary cleaning will pay, since it saves wear and tear on the drawing dies, and it is really just as easy, and cheaper in the long run, to clean wire well as ill.

(3) Wire which has already received some preliminary drawing, or "ripping" as it is called, and returns to be recleaned after heat-treatment or annealing should require very little pickling, because no wire should be allowed to scale seriously in a modern annealing or patenting furnace. When the preliminary pickling has been carried out efficiently, immersion in cold acid for a period of from 5 to 15 minutes should be sufficient to clean wire which has been properly heat-treated. Such wire will have a much smoother surface than the hot-rolled rod, and there should be no pockets or embedded scale. Pitting of the wire by over-pickling is to be avoided at this stage, whereas, in the initial cleaning of the rod, pitting is less serious than the incomplete removal of scale. Some pitting of the rod there must be, since the metallic surface of a hot-rolled rod after the removal of all scale is inevitably rougher than that of a drawn wire, but drastic pitting of the steel by acid attack after the removal of the scale can now be avoided by the use of "inhibitors."

For the foregoing reasons, then, rod pickling should be a more drastic operation than that of wire. The complete removal of scale is essential in both cases, but in the case of wire this should not involve drastic attack, while in the rod it may; and

drastic pickling even when it involves some roughening of the surface is to be preferred to the incomplete removal of scale.

Hot vitriol is the most commonly used pickling liquor for cleaning wire rods. It is certainly the cheapest, especially in the United States, where it is a by-product, and even in this country it is cheaper when used hot than hydrochloric acid, which being a gas dissolved in water is more easily driven off and wasted by evaporation.

In general, whether hydrochloric acid or vitriol is used, the important points to be noted are:

(1) The acid should not be allowed to become too weak or too old and dense. Hot weak tanks are to be specially avoided.
(2) A good inhibitor should always be used.
(3) Tightly bound coils should never be put into pickling tanks.
(4) The conditions of acid strength, temperature and density, and time of immersion should be continually controlled and kept within limits which have been found most suitable for each type of steel.
(5) When high carbon rods for high-grade wires are being cleaned and there is danger in pitting of the surface or of hydrogen brittleness, the complete immersion in acid should be avoided as far as possible, and banging machines should be utilised.

Wire cleaning, as already explained, should be a much less drastic operation, and cold acid is generally used for such pickling, especially in the finer gauges. In this country and on the Continent hydrochloric acid is generally used, although vitriol is frequently used in the United States.

The most satisfactory pickle is really a solution of ferrous chloride or sulphate, and hydrochloric acid or sulphuric acid. A pickling solution of free acid and water only is sluggish in action and develops a black scum on the wire, particularly when the acid contains arsenic, the content of which in acids for pickling should never be more than 0·005 per cent. The acid strength with hydrochloric acid should be between 5 and 10 per cent., and the density should not exceed 1·25. When the liquor becomes too dense the pickling action is seriously retarded and the addition of fresh acid has little or no effect, so that it is simply wasted. When the density reaches 1·25 the pickle may be gently heated until the acid strength is sufficiently reduced to permit of throwing to waste without serious loss, or the upper half may be removed to another tank and made up again with fresh acid and water.

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[4] Stead, "The Detection of Burning in Steel," *Journal of the Iron and Steel Institute*, 1915, No. 1, p. 398.

[5] Giolitti, *Heat-Treatment of Soft and Medium Steel.* Translated by Thum and Vernaci, McGraw Hill Book Co., New York.

CHAPTER III

WIRE-DRAWING

THE COLD-WORKING OPERATION

It has been pointed out already that most metals and alloys can be moulded or shaped by hammering and that they possess under certain conditions a degree of plasticity which is akin to a fluid form. Liquids will flow through a hole in a vessel by virtue of their own weight, and, if pressure is applied, the rate of flow is increased. Similarly, certain very soft metals such as lead and Muntz metal can be forced by pressure to flow through an orifice, and a practical example of this property is to be found in the manufacture of lead piping, the process being called "extrusion."

Most metals, however, are too rigid to be deformed in this manner and advantage has to be taken of other methods. The pressure to cause the deformation has to be applied indirectly and in such a way that its action is severely local. In the making of wire this is accomplished by means of the wire-drawing die. This in its simplest form is a tapered hole set in a hard material. The semi-angle of the taper varies from about 4° to 12°, depending chiefly upon the type of material which is being drawn and the reduction given per pass. Fig. 6 shows, in a simple form, the forces which operate upon a material when passing through a die. P represents the pull on the wire and R the reaction of the die surface. It will be seen that the flow of the metal is caused by the circumferential pressure or reaction of the die induced by the direct pull, and upon this principle is based the whole of the art of wire-drawing in its many diverse forms. (A more detailed consideration of the forces acting during the drawing process will be given at a later stage.)

However, although the principle seems to be very simple, it must not be thought that the evolution of the wire-drawing process has been an easy matter. It has been a very halting and slow progress from the earliest form of draw bench to the modern continuous wire-drawing machine, partly due to the necessity of overcoming prejudices, but mainly due to the thousand and one difficulties which have had to be overcome by dint of trial and patient experiment throughout the years.

When a metal is drawn into the form of a wire, or cold worked in any way, its physical properties are changed in a greater or lesser degree depending upon several factors such as the original condition of the material, the amount it has been deformed and the manner in which it has been cold worked, etc. These changes are usually gradual, and they can be controlled by the practical wire-drawer so that almost any desired properties can be given to the finished material. Usually

it is not possible to obtain these desired properties by passing the metal through one die, but it has to be done in a series of stages or steps called passes or draughts, and this is accomplished by drawing the metal through successive dies, each one having a smaller bore than the preceding one.

In the early days of the art wire was drawn by hand, or on long benches where the motive power was supplied by hand, and, in form, these benches were not

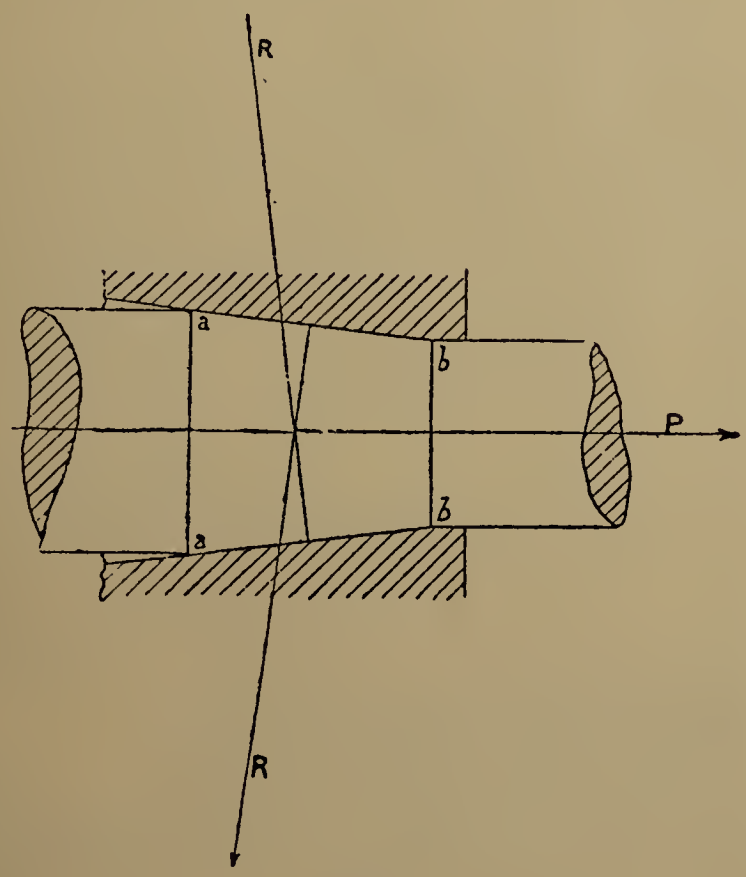


Fig. 6

unlike the bar-drawing bench of to-day, except, of course, that in the case of the latter, the bar is pulled through the die by mechanical power. It is interesting to note in passing that wires of the precious metals, gold, platinum, etc., are still drawn by hand.

Perhaps the greatest single advance made was the introduction of the drum or block which rotates, and round which the wire is wrapped as it is pulled through the die. In this way it is possible to draw long continuous lengths of wire which vary very little in properties from end to end. Although this method has been known for at least three hundred years, the single-holing block, as it is called, is still used to-day in many wire-drawing shops for the production of the thicker gauges of wire and for special materials where great care has to be taken, but during the last few years, for the production of the ordinary grades of wire, the single-holing block has been superseded to a large extent by the various forms of continuous machines.

Fig. 7 is an illustration of a heavy drawing block designed by Messrs Crossley, Ltd., of Cleckheaton, and Fig. 8 shows an outline of another heavy bench designed by Messrs H. Saville, Ltd., of Stetford. Both these are single holing machines —*i.e.* the wire passes through one hole between the swift and the block.

The drum or block which is used for the drawing of thicker gauges of wire

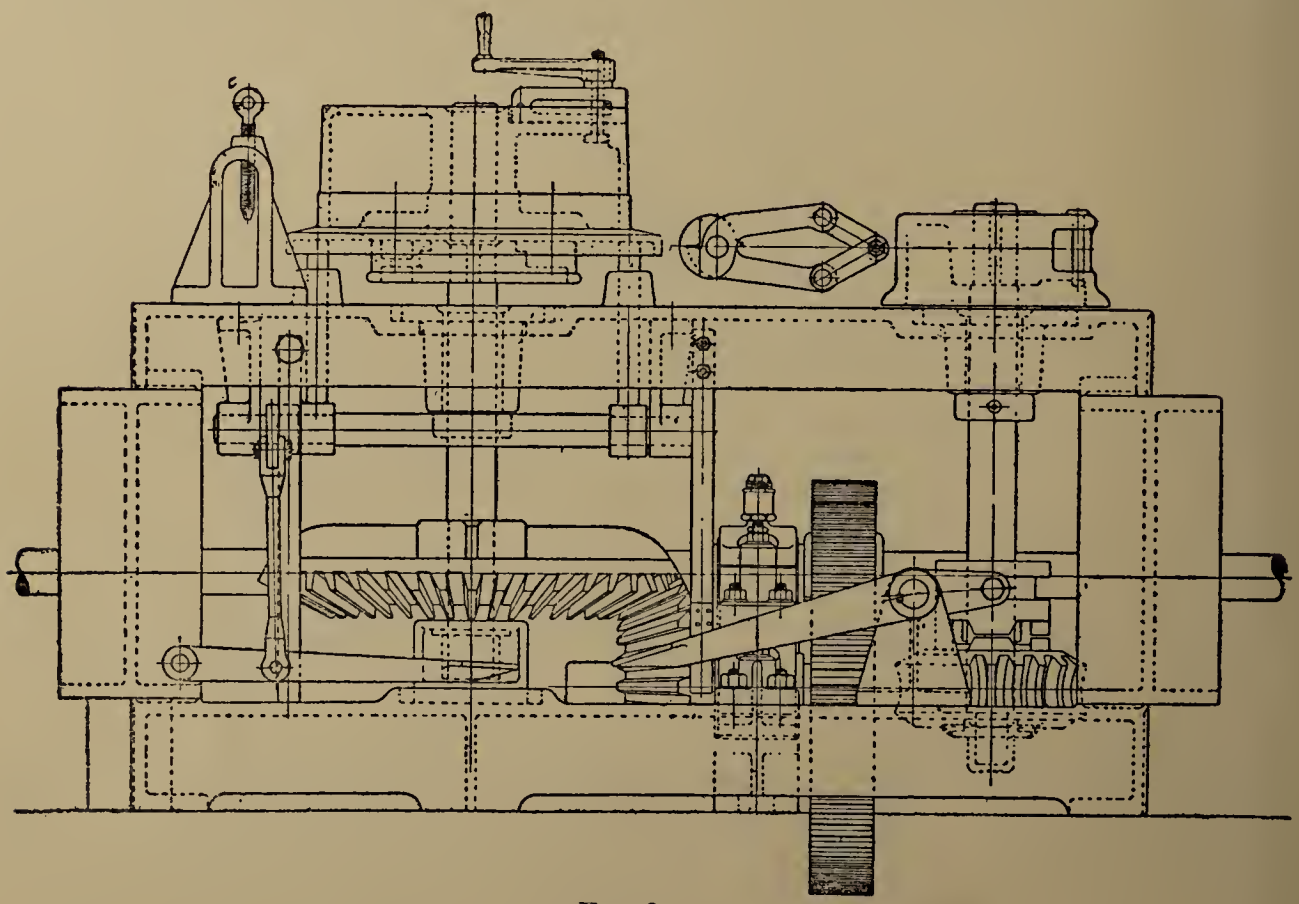
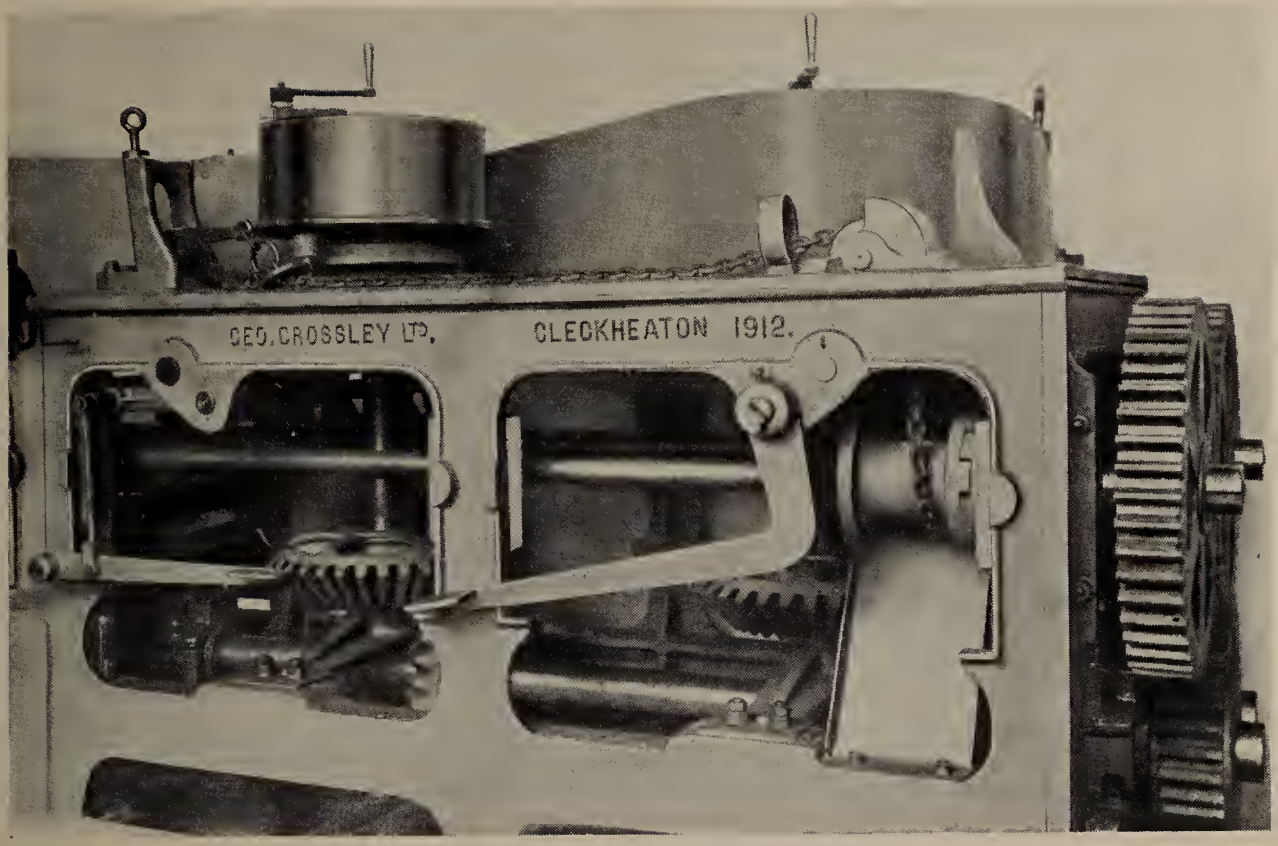


Fig. 8

varies from about 22 to 28 inches in diameter. It revolves on a vertical spindle, which is driven by various methods according to the design of the machine. Thus the machine of Messrs H. Saville may have direct coupled electrical drive to the spindles controlled by either electro-magnetic or by friction clutches, or like Messrs Crossley's machines the blocks are coupled to the main or subsidiary shaft by means of bevel gears, and are brought into play by means of dog clutches operated by foot pedals. The "pulling-in" capstans are usually run off subsidiary shafts. In the larger wire-drawing shops it is usual to have a large number of blocks—ten to twenty—driven by a single shaft. The block is tapered upwards and generally has a step at the bottom; this ensures that when some five or six turns have been coiled on the block, they commence to slip upwards and lie loosely without riding over each other which would cause crushing and bruising of the wire; also the coil is easy to remove at the end of the operation. Such a block is known amongst wire-drawers as a "shooting block."

On the bench is fixed the die or draw-plate—a plate containing several holes,



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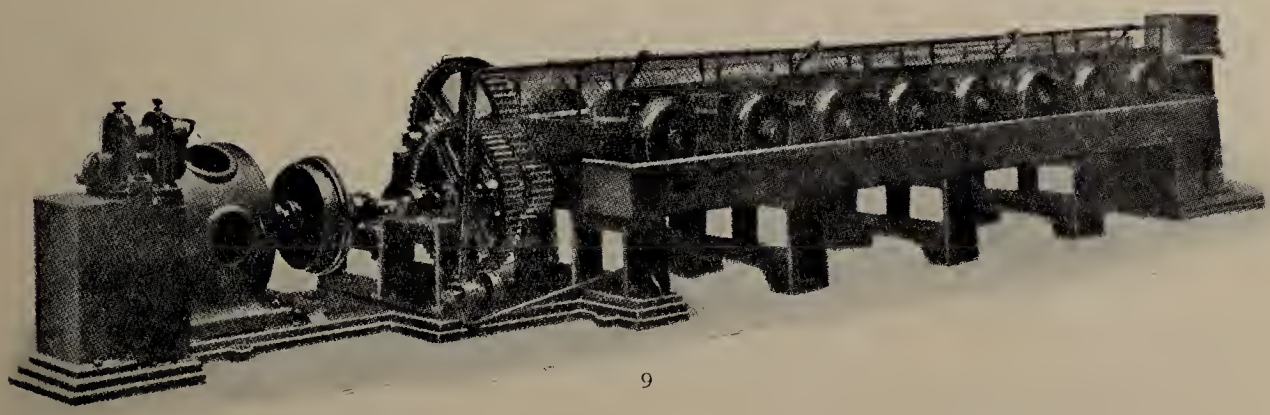

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Fig. 7. CROSSLEY'S SINGLE-HOLING MACHINE

Fig. 9. SAVILLE'S CONTINUOUS WIRE-DRAWING MACHINE FOR 9 PASSES

usually about eighteen—and opposite are a pair of tongs attached to either a chain or a cable which is actuated by the small capstan to which reference has already been made. The wire-drawer points one end of the coil of rod so that a small part will pass through the die. He can do this pointing by several methods—filing, holding in a flame and pulling it when red-hot, but it is usual to use a small roller pointer, one of which can be seen in the front of Fig. 12. In the case of dry drawing the pointed end is passed through a soap box or bag (soap being a lubricant), passed through the die, and gripped by the tongs. A short length is slowly pulled through the die, and this portion is gauged to see if it is correct to size and sufficiently round. If it is satisfactory the point is released from the tongs and fixed to a small vice on the upper edge of the block. The block is then thrown into gear, and in revolving pulls the remainder of the rod through the die. This briefly describes the principle of the process. The actual operations may differ in detail according to the size and nature of the material and the type of machine used. As has been stated previously, continuous wire-drawing machines are taking the place of the single-holing block for the production of ordinary grades of wire, and of these there are three main types illustrated in Figs. 9, 10, and 11.

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In the continuous process the wire passes through several dies before being wound on to the block. When wire is reduced in diameter it increases in length as its volume remains constant, and it will be obvious that some provision must be made for the extra length to be taken up after each successive die. In the first type of machine (Fig. 9) this is accomplished by wrapping the wire round a power-driven barrel or drum between each die, the speeds of the individual barrels being increased at each stage. The tension on the wire between two dies is regulated by the number of turns round the barrel, the surface of which is sometimes made of some comparatively soft alloy so that slip may take place without damaging the wire. Unfortunately this slip cannot be entirely eliminated, so that removal of the drawing coat often takes place and subsequent trouble is experienced, it sometimes being impossible to draw to the final size. Another disadvantage is that the machine is restricted to definite drafting stages at each pass according to the setting of the machine, there being no flexibility in the speeds of the intermediate drums, and this entails careful setting of the intermediate dies. These disadvantages are making the machine obsolete.

In the second type of machine (Fig. 10) three or four blocks are superimposed on one spindle. The wire is first passed through a draw-plate, then once or twice round the first block, back round a pulley, through the second draw-plate, round the second block, and so on to the finishing block, which is at the top of the spindle. Within these blocks are two differential sun and planet motions, and it is to these motions the blocks are connected and not to the spindle. When the machine is idle the blocks are quite loose and can be turned by hand either way, but when the spindle is put into motion the blocks are carried round at the same speed. Should any pressure be put on the first drum and acceleration of speed takes place in the other two, and vice versa, consequently the speeds of the wires in the various sections

tend to be proportionate. Even in this type of machine slipping has not been overcome, and consequently the wire may be damaged, and hence it is open to similar objection as the machine described above. However, recently, considerable improvements have been made in the design of this machine leaving very little to be desired.

In the third type of machine the disadvantages due to slipping have been overcome by accumulating a surplus of wire on each block so that the process is, in effect, continuous single-holing. In one machine of this type, made by Messrs Sir James Farmer Norton, each block is driven by spiral reduction gears coupled direct to its own motor, the individual motors being fixed at the rear of the machine. Each motor is individually controlled, and its speed may be varied, the controls being simple foot pedals, consequently the tension can be kept uniform throughout; but should the tension on the wire become excessive in any part of the train an automatic trip comes into action and stops the whole machine. The threading-up of the machine is simple, and if the ends of separate coils are welded on to each other the machine can run for a whole shift with very little attention.

Another machine of the same type, made by Messrs Barron & Crowther, is illustrated in Fig. 11. In this case only a single motor is used.

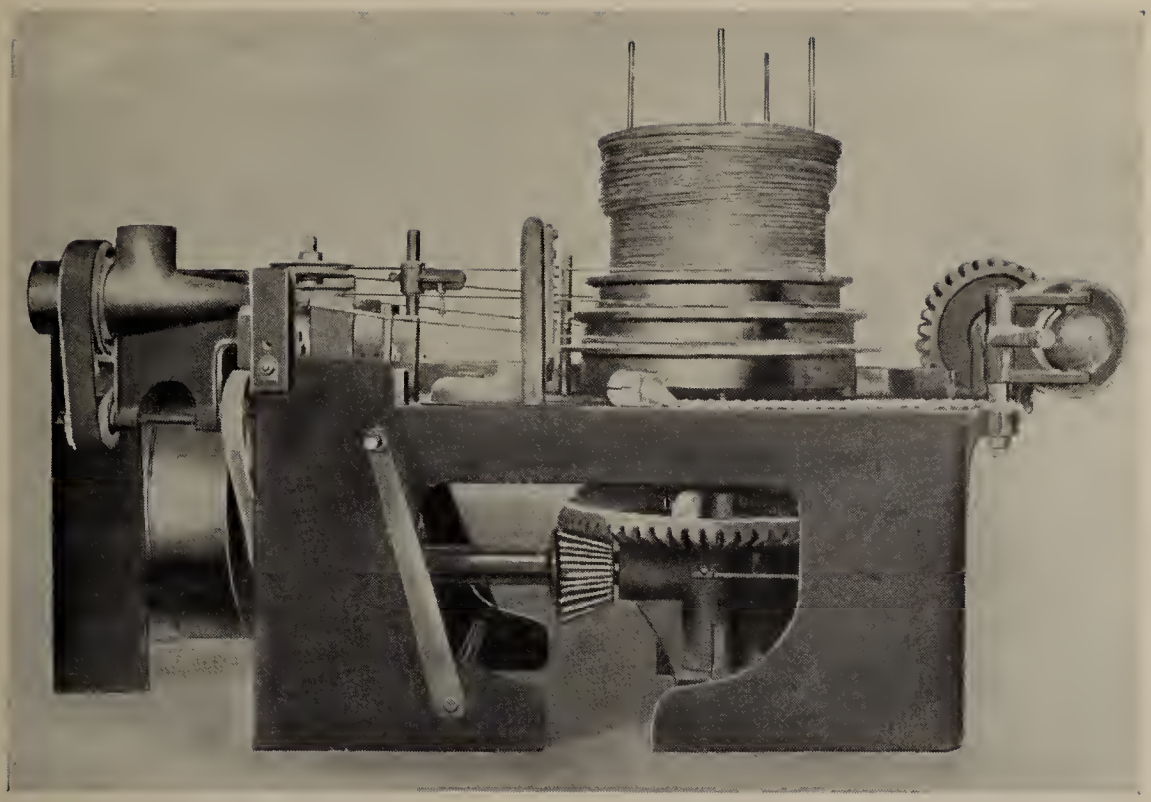
Prior to the advent of this type of machine opinions differed as to the advantages of continuous drawing against single-holing, although continuous drawing has been in use for many years for the manufacture of fine wire. With single-holing and large gauges of wire very little time is taken for the operation, and its chief drawback is the enormous amount of lifting required. The chief drawback of continuous holing is the time taken to thread-up the machines, but with the finer gauges of wire a machine when threaded-up will run for as long as five or six hours, and it will be seen that one operator can look after several machines. In the type of machine illustrated in Fig. 11 these objections seem to have been overcome.

The foregoing paragraphs have given the chief essentials of the wire-drawing process, and it is now proposed to deal, in more detail, with certain aspects such as the die or draw-plate, wire gauges, and reduction per pass, drawing speeds, lubrication, and wet and dry drawing.

THE DIE OR DRAW-PLATE

The die, draw-plate or wortle-plate, is the essential tool in wire-drawing. Short lengths of wire can be drawn with no other apparatus than the die and a pair of tongs. One would naturally think at first that the most suitable steel for a draw-plate would be an ordinary die steel, such as Huntsman's steel, in the hardened and tempered condition, but rightly or wrongly such steels are not usually used for the drawing of round wires. Possibly this is due to the traditions of the trade in this country, where wire-drawing is considered to be a highly skilled operation, and where, too often, the wire-drawer works up his own dies and keeps them in condition.

In Canada and in the United States chilled iron dies are used in the drawing of the cheaper grades and heavier sizes of wire, but in Europe the usual die is made of



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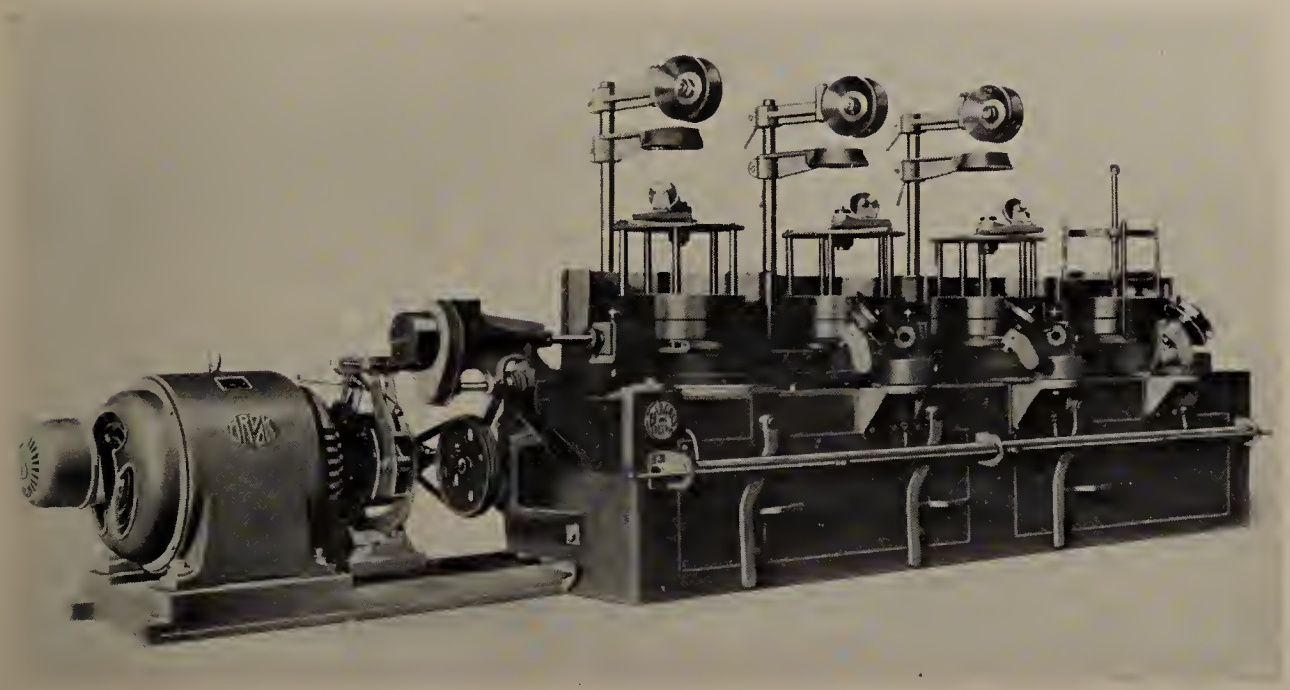

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Fig. 10. BARRON & CROWTHER'S THREE-HOLING CONTINUOUS DRAWING MACHINE

Fig. 11. "BARCRO" NON-SLIP FOUR-HOLING MACHINE

high carbon cast crucible steel with usually 1·6 per cent. of carbon and occasionally higher. This in many respects is similar to the chilled iron, but it has the advantage that it can be forged hot and is sufficiently malleable to be battered when cold. Thus the wire-drawer can reduce a hole that has been enlarged by a previous drawing, by battering it on the exit side and reamering it out to the correct size. The structure of an ordinary carbon steel draw-plate is shown in Fig. 13, and it consists mainly of intensely hard cementite (Fe_3C), the white constituent, with sufficient pearlite, dark, to give the necessary malleability for battering. The cold hammering round the hole hardens up the pearlite areas so that for all practical purposes the actual bearing surface is the very hard carbide of iron. A typical analysis of a plain carbon draw-plate is as follows:

Carbon	*Silicon*	*Manganese*	*Sulphur*	*Phosphorus*
1·97	0·12	0·40	0·009	0·014

Recently draw-plates have been improved by the introduction of chromium and tungsten steels; molybdenum steels have also been tried. A typical analysis of an alloy steel plate is:

Carbon	*Silicon*	*Manganese*	*Sulphur*	*Phosphorus*	*Chromium*	*Tungsten*
2·65	0·042	0·3	trace	0·022	14·27	3·8

High silicon in such a material is liable to lead to the precipitation of graphite during the heatings and annealings, and, for some reason, forging such a steel at too low a temperature facilitates this precipitation.

The size and shape of the draw-plate varies with the size of wire being drawn. Rods and wires down to about 18 S.W.G. are drawn through plates of the type shown in Fig. 14, the size of which will be about 12 by 5 by $1\frac{1}{2}$ inches. The holes in a single plate are all of the same size, successively different draw-plates being used for each pass. Wire smaller than 18 S.W.G. is drawn through a rectangular plate containing six holes, which are first punched hot and finally sized and shaped correctly, when cold, with hardened and tempered-tapered punches. Wortle-plates are usually supplied by the maker with the holes already punched, but the wire-drawer has to shape them accurately before use. When a coil of wire has been passed through a hole the latter becomes enlarged, and, if the die is made of chilled iron, it can be used again only for drawing wire of larger diameter; but, as indicated previously, steel dies may be closed up again by battering, so that after reamering and testing they may be used again for wire of the same size. Each hole in the plate is used once or twice in this way until it is no longer possible to batter them up cold, but they can be reduced by hot battering and used over again. Thus a plate containing eighteen holes can be made to last for a considerable time; but, unfortunately, all this battering and reamering takes up a good deal of the skilled wire-drawer's time, although he may have machines drawing wire at the same time. More efficient methods of working are gradually being introduced into works in this country, copying American practice, where the actual drawing is done

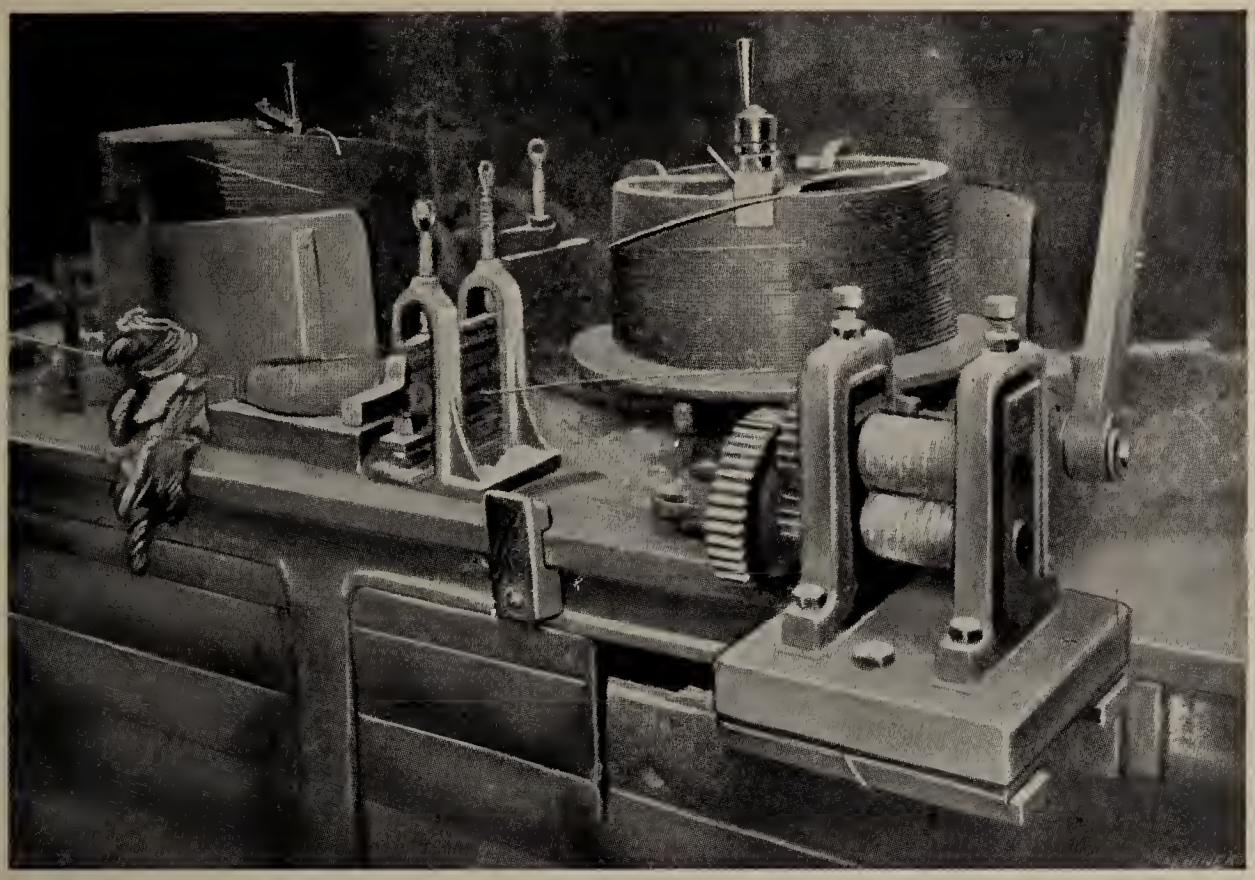
by unskilled and semi-skilled labour, the dies being prepared for them in a separate department by skilled men. Very fine wire is drawn through button dies with a single hole. As a rule these dies are not made of steel, but of diamond, and more recently tungsten-carbide, set in brass or other metal as holder.

During the last twenty years a large amount of experimental work has been carried out with new materials in the form of wire-drawing dies. Manganese steels of the Hadfield type (*i.e.* those containing about 12 per cent. manganese and 1 per cent. carbon) have been tried, but although it might be thought that such a material would be ideal for the purpose, the results obtained were disappointing. Attempts have been made to use nitrided dies, but details as to their performance are meagre, so no conclusions can be drawn as yet about their capabilities. The most promising results have been obtained with dies of the tungsten-carbide type marketed under various trade names such as Widia, Carbaloy, etc., and the carbides of other elements such as tantalum, silicon, etc. These carbides are extremely hard materials approaching the hardness of diamond, which is the hardest substance known. The dies vary somewhat in composition as the carbide is sintered with small amounts of iron, nickel, and cobalt, etc., but the essential hard material is the carbide, and it will be seen that the condition is analogous with that of the cementite or iron-carbide in the ordinary steel die.

Although these dies have proved to be very satisfactory, they have certain disadvantages. They cost more initially than steel dies, and, as they wear, they cannot be battered down again and reshaped to the original size, but have to be ground to the next larger size. They are rather susceptible to the condition of the rod, but more so to thermal stresses set up internally if the temperature is rapidly altered, a condition which can occur during the drawing process, and this may cause flaking to take place and consequent spoiling of the die and the wire. Hence a certain amount of care is necessary in the use of these dies, and some form of cooling device seems to be essential.

One very interesting point is that in all cases examined, the power consumption with tungsten-carbide dies is considerably lower than with the corresponding steel dies, and sometimes very appreciably so. It is stated that it is no exception to find an economy of the order of 30 per cent. in the power used when tungsten-carbide dies are substituted for steel dies. A further point in their favour is that compared with steel dies the length of service is very much greater before resetting is required, provided they are used carefully. Another good point in their favour is that the surface finish of the wire is much better when using this type of die.

Such experience as the author has had of tungsten-carbide dies indicates that in the near future they will supersede entirely the old steel and chilled-iron dies, at least for the drawing of all intermediate and final sizes of wire. The steel and white-iron die may continue for some time at least for "breaking-down" wire from the rod, since the rough surface of the latter is not conducive to die life. Much greater care in preparation would be required if the more costly carbide dies were to be used for the initial stages. It is easier and cheaper to use the ordinary steel



12 (Reproduced from "*Machinery*" by permission)

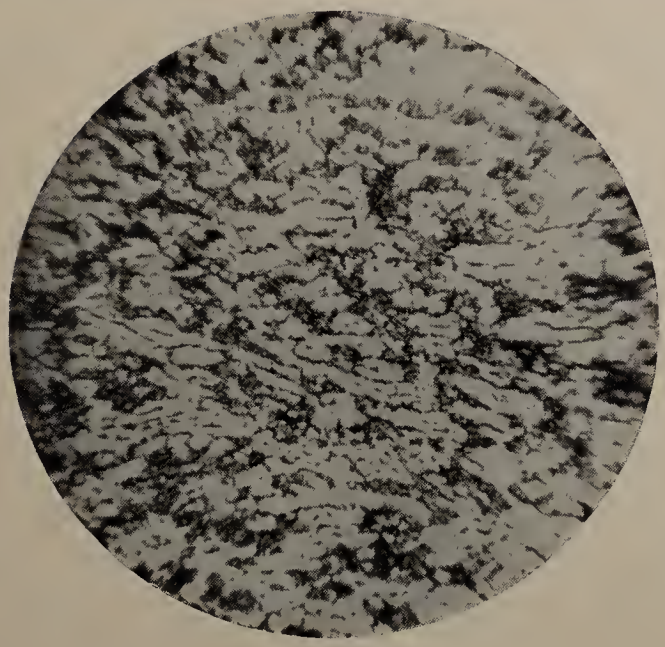


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Fig. 12. WIRE-DRAWING BLOCK WITH POINTING ROLLS IN FOREGROUND

Fig. 13. STRUCTURE OF WIRE-DRAWER'S PLATE

die to bear the brunt of the shock attack involved in the breaking-down process. Nevertheless, the efforts to establish the use of tungsten-carbide dies even for the initial stages of the drawing process have already focused attention on those factors which make the first pass a critical one. Since this is a matter of considerable importance whatever form of die material is used, it may be well at this point to discuss the more important of these factors.

No matter what die material has proved satisfactory, it has been found that the smoothness of the surface has an extremely important bearing on the wearing qualities of the material. It has been stated that the smoothness and flatness of the surface determines the final results more than the accuracy of shape, provided that the shape is reasonably close to that which experience has shown to be correct, and that the nature and smoothness of any surface determines the wear-resisting qualities more truly than even hardness—a point which deserves serious consideration and which will be mentioned again later in the discussion of the wear-resisting properties of rope wire (Chapter VIII.). However, the utmost care and precision in finishing the surface of the die cannot offset the defects in the surface of the rod or wire, since it is the frictional forces acting between the two surfaces which largely determine the life of the die and the power required to draw the material. The surface of hot-rolled rod is always rough compared with that of drawn wire, and this fact alone, quite apart from any other surface defects which may be present, constitutes one of the difficulties in the preliminary drawing. The wire-drawer using steel or chilled-iron dies overcomes this difficulty not only by efficient lubrication, but by using a wider angle of approach in the "breaking-down" die and rounding or blending the approach into the bearing. In general it can be said that "short bearings" are preferred at this stage.

Most of the other factors which make the first two or three passes in drawing troublesome, such as the presence of scale due to inefficient pickling, inclusions of an abrasive character, spills, cracks and laps, etc., have been dealt with already in Chapter II. When tungsten-carbide dies are used these factors play a very large part, and, as has been mentioned above, tungsten-carbide dies cannot be used again for drawing the same size when once they have become worn and have been re-polished, consequently they would very soon become useless and hence very expensive. However, research into the problem is going on and no doubt a satisfactory solution will be forthcoming in the future.

Reference has already been made to the shape of the die, and it was also mentioned that "short-bearing" dies are usually used for the "breaking-down." The shape, the angle of approach, and the bearing of the die are very important factors in the efficiency of this tool. In the drawing of steel wire the shape is almost invariably conical, but a section taken through the hole generally shows a small parallel or nearly parallel portion at the exit end, particularly in the case of dies used for the drawing of harder steels. This portion is made by the final "set piece" or punch which leaves sufficient length of the same size as the reduced diameter in order to avoid "pulling-out," that is the edge of the taper breaking away and

spoiling the die and the finished wire. Radial tapers, that is trumpet-shaped dies, are rarely used in the drawing of steel wires except for light reductions, although some of the diamond dies are of this shape.

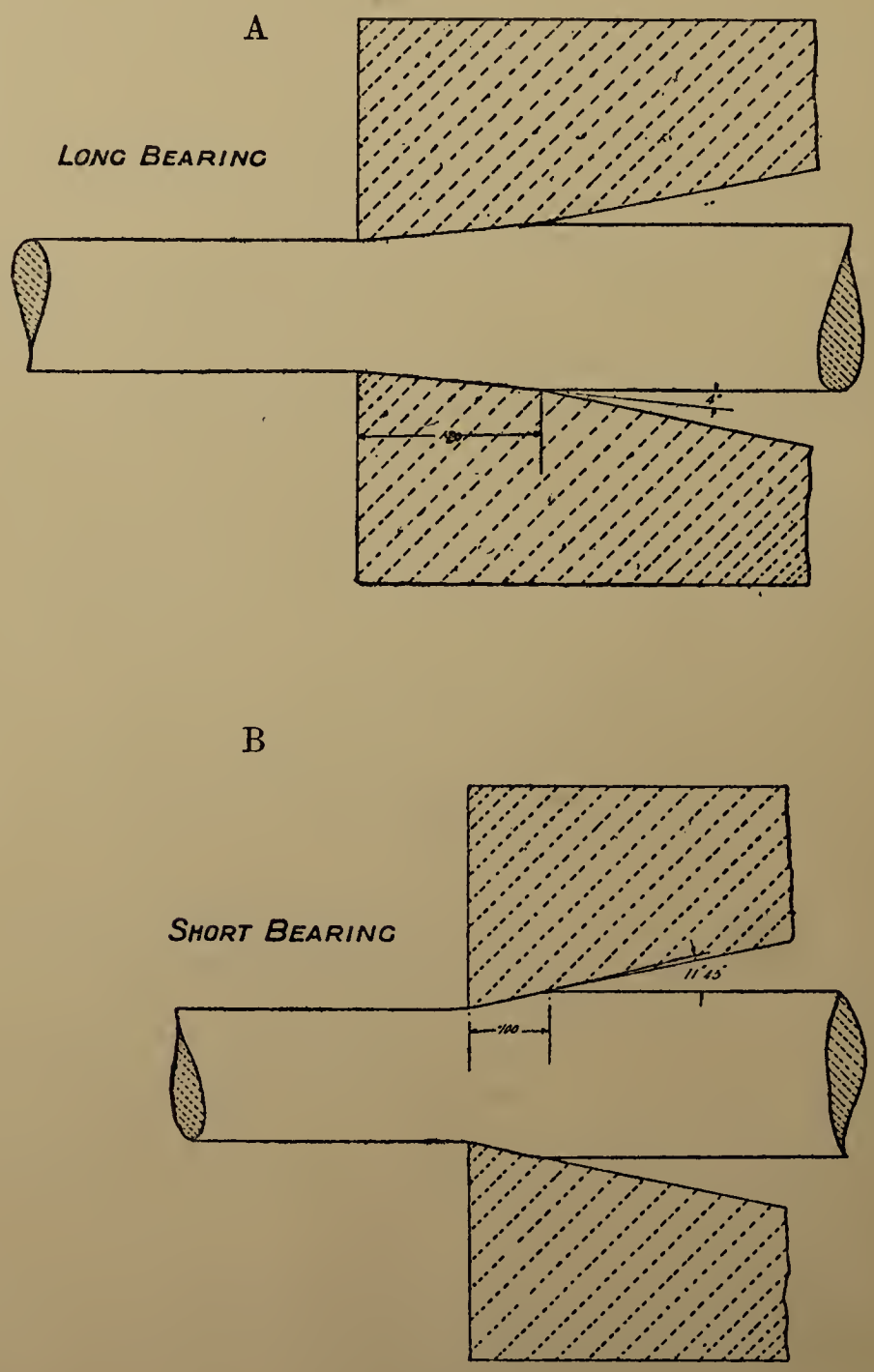
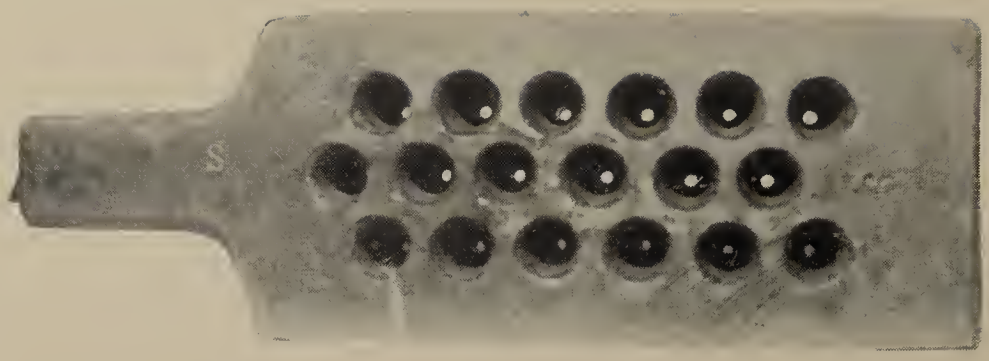


FIG. 15

In Fig. 15 are shown typical bearings drawn to scale, A being a so-called long bearing—*i.e.* a greater length of material, and consequently surface area is in contact with the die. B is a short bearing. In Fig. 16 are shown two sections obtained photographically. The length of the actual bearing, including the tapered

Plate VI.



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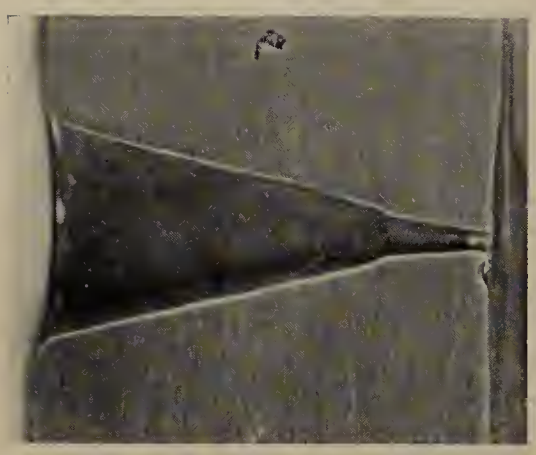

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Fig. 14. WIRE-DRAWER'S PLATE

Fig. 16. SECTIONS THROUGH DRAWING DIES SHOWING TYPICAL BEARINGS. Full Scale

portion, depends upon the size of the wire being drawn as well as upon the material. On wire of about 5 or 6 S.W.G. it will vary from about $\frac{1}{4}$ to $\frac{1}{16}$ of an inch, according to the material and its surface condition.

Within fairly wide limits, such as have already been determined empirically by the skilled wire-drawer and explained mathematically and confirmed experimentally by various investigators, the die angle does not seriously affect the quality of the wire produced, provided the reduction given is not too great. In other words, the change in properties is dependent upon the amount of cold working received or the reduction it has suffered, and not upon the method in which the reduction has been carried out—that is, the variation of the die angle. But variation of the die angle does affect the power consumption and the life of the die, because of the frictional changes involved. The conclusions reached by Thompson and his co-workers point to a semi-die angle of from $5\frac{1}{4}°$ to $6°$ to require the least power consumption when drawing intermediate-sized steel wires, and for drawing austenitic steels the value is between $5°$ and $5\frac{1}{2}°$. The experience which the author has deduced from the observation of wire-drawing practice is that short-bearing dies with a semi-angle of about $11°$ are preferred for breaking down from the rod, because of the rough surface of the material and the consequent large amount of friction. On the other hand, for finishing hard wire a long bearing may be used, because the wire has a smooth surface which is well impregnated with coat and lubricant, and hence will stand more pull because the frictional forces are less. In some cases the semi-angle may be as low as $4°$, although the figure of $6°$ is probably the more usual. Where the reduction in a draft is small, a smaller angle is necessary, especially with hard materials, in order to obtain the necessary length of bearing, otherwise pulling out would occur. As a result of his investigations Thompson suggests that a radial taper die should be used for roughing down from the rod. This would give the necessary high angle of die when the metal first enters, but decreasing to about $6°$ at the exit. As far as is known, this suggestion has not been tried out in practice, but the condition is nearly realised by the practical wire-drawer, who usually sets a small portion of the exit end of his roughing die to an angle of about $6°$.

In general, it might be said that the known conditions for the use of steel dies are as near perfect as it is possible for them to be, but further research may bring other factors to light. The progress of the synthetic carbide die has been rapid, and as the coefficient of friction between the steel and this type of die is less than with a steel die less power is required to draw the material. On first thoughts it might seem that by increasing the die angle and using the same power as previously it might be possible, by altering the draughting, to cut out one pass, and thereby establish considerable saving in costs. This is problematical, because changes in draughting would alter the properties of the finished material, as will be seen later. The question of lubrication is receiving much attention, but this very important factor is to receive our consideration later. However, it is to be expected that within the next few years considerable improvement will have been made to this very important tool, the die, which should result in the production of better and cheaper wire.

THE WIRE GAUGES AND REDUCTION PER PASS

When referring to the size of a wire the layman generally expresses it in one term only, its diameter. If he is of British nationality he will express this as best he can to the nearest vulgar fraction—$\frac{1}{8}$ inch, $\frac{3}{16}$ inch, etc.—indeed, if the diameter is given to him in any other term he will mentally change it into a vulgar fraction. The scientific man will express it in decimals of an inch, while the German and Frenchman will state it in terms of millimetres.

The practical wire-drawer does none of these things; he gives it a number known as its "gauge number," and there are reasons for this. In this country the decimal system is not generally known and vulgar fractions are cumbersome; more mistakes are made with the decimal system usually by the misreading of the decimal point or the omission of an essential 0. But to the wire-drawer the gauge number means more than its size; he has to think not only of its present size, but of what size it was before drawing and of what size it is likely to be. In other words, he has to consider its reduction in terms of cross-sectional area, not in terms of diameter, and this is what the gauge system enables him to do unconsciously. Unfortunately, not one of the many gauge systems invented is perfectly satisfactory, and a great deal of confusion has arisen, so that the present tendency is towards the designation of wire sizes by diameter, either in decimals of an inch or in millimetres; but it is almost certain that the practical wire-drawer will continue to use the gauge system and speak of the wire being drawn a size or a size and a half, until the systems of draughting become more standardised with the more general use of continuous wire-drawing machinery. Particulars of the more important gauge systems in use are given in the Appendix.

As has been inferred above, these gauge systems have apparently been constructed on the principle that wire should be reduced a definite similar amount from any one gauge to the next in each pass—*e.g.* the reduction in cross-sectional area when passing from, say, 6 S.W.G. to 7 S.W.G. will be the same as when passing from 7 S.W.G. to 8 S.W.G., and so on. Although this is no longer strictly adhered to in practice, the reduction in terms of gauges forms a useful standard, and the finest grades of wire are still reduced in this way. Probably the most usual reduction nowadays for patented steel wire is from $1\frac{1}{4}$ to $1\frac{1}{2}$ S.W.G. per pass, while mild steel is often reduced two or even three gauges per pass. This increase in the stages of reduction has not been introduced with the idea of improving the properties of the wire, but solely with the object of reducing the working costs. However, it must not be assumed that the increase in percentage reduction at each pass involves any serious deterioration in the properties and quality of the wire; it has become possible because of improved heat treatment processes, which have enabled steel to stand more drastic cold work without damage.

The question of the reduction per pass or the system of draughting is an exceedingly interesting and important one. It has been pointed out previously that the

object of drawing is to produce wire of given dimensions with or without a specified tenacity. In the former case—that is, with a material belonging to Class I.—the programme of draughting depends upon the following points:

(1) What reduction the material will stand without damage at each pass.
(2) What is the most economical system of drafting.

For example, suppose a certain metal is sufficiently ductile to stand a reduction of at least two gauges at each pass, and has to be reduced from No. 5 S.W.G. to 23 S.W.G. It might be reduced in several ways, and three possible systems are given in Table 1, p. 44. These systems are purely hypothetical and are not intended to represent actual programmes adopted in practice, but simply to illustrate heavy, medium, and light holing respectively. Probably none of these programmes would be adopted in practice, but a compromise would be made depending upon the annealing plant, pickling facilities, and drawing machinery available. With single-holing machines drawing the larger gauges the heavy or the medium holing system would be used, while the smaller gauges might be drawn four light passes in one operation on a continuous machine. It should be pointed out that only the most ductile metals will stand such a heavy reduction as two gauges in one pass, and some of the harder metals will only stand one light pass between each annealing.

As an example of the effect of varying the reduction in drawing, the reader is referred to Table 13, p. 91, where the physical properties of armco iron wire, light and heavy holed, are compared.

In dealing with patented steel wire, however, there is probably more scope for scientific control of the drawing programme, because with this material it is not only reduction in size that is required, but the highest possible efficiency in the subsequent physical properties is desired. It might be thought at first that this is a simple problem involving merely a diminishing reduction at each pass as the wire increases in strength and loses ductility, and that the less the reduction at each pass the better will be the finished product. This simple process not only ignores the economical aspect, but is based on an assumption that is not necessarily true —*i.e.* the more gradually a wire is reduced the better. To produce the same tensile strengths it is necessary to give a greater overall percentage reduction when light holed compared with heavy holed, consequently this means starting with thicker rod in the former case to reach the required tensile strength. The problem, then, is to find when heavy holing can be employed and when it is unsafe. This actually is an extremely complex problem and one which is intimately related to the mechanism of plastic flow. Until the physicist has explained this satisfactorily the question has to be tackled on empirical lines.

Such experiments as the author has so far carried out have indicated that at certain stages in the drawing down the wire can be heavy holed with safety, but at others it must be treated gently by light holing. Nor is it a matter of making the reduction more gradual as the wire becomes harder, but rather a matter of how its structure is suited at each stage for withstanding cold work. Whether it will

TABLE 1

Showing Three Hypothetical Drawing Programmes on the same Material

1 *Heavy Holing*		2 *Medium Holing*		3 *Light Holing*	
No. of passes	S.W.G.	No. of passes	S.W.G.	No. of passes	S.W.G.
0	5	0	5	0	5
1	7	1	$6\frac{1}{4}$	1	$5\frac{3}{4}$
		2	$7\frac{1}{2}$	2	$6\frac{1}{2}$
2	9			3	$7\frac{1}{4}$
		3	$8\frac{3}{4}$	4	8
3	11	4	10		
Anneal				5	$8\frac{3}{4}$
4	13	5	$11\frac{1}{4}$	6	$9\frac{1}{2}$
		6	$12\frac{1}{2}$	7	$10\frac{1}{4}$
5	15	Anneal		8	11
		7	$13\frac{3}{4}$		
6	17	8	15	9	$11\frac{3}{4}$
Anneal				10	$12\frac{1}{2}$
7	19	9	$16\frac{1}{4}$	11	$13\frac{1}{4}$
		10	$17\frac{1}{2}$	12	14
8	21			Anneal	
		11	$18\frac{3}{4}$	13	$14\frac{3}{4}$
		12	20	14	$15\frac{1}{4}$
9	23			15	$16\frac{1}{4}$
		13	$21\frac{1}{2}$	16	17
		14	23		
				17	$17\frac{3}{4}$
				18	$18\frac{1}{2}$
				19	$19\frac{1}{4}$
				20	20
				21	$20\frac{3}{4}$
				22	$21\frac{1}{2}$
				23	$22\frac{1}{4}$
				24	23
9 passes and 2 annealings		14 passes and 1 annealing		24 passes and 1 annealing	

be possible to obtain rules which will be consistent remains to be seen, but the problem seems to be worthy of further research.

It may be of interest to compare the conclusions to which the author has been led from study of the physical properties and microstructures of wires at each stage in drawing with those of a highly skilled wire-drawer based upon the experience of a lifetime. The author found that the first pass had usually a severe effect upon the steel, being something in the nature of a shock to the virgin rod, and therefore should be as light as possible. At the stages of the third and fourth passes the wire was found to be inured, withstanding the rough treatment without great disturbance. This suggests that heavy reductions could be given at these stages. The reductions at the subsequent passes depend upon the type of wire required; thus for hard wire they would continue heavy, but for tough or ductile wire they would become lighter. Compare these with two actual draughting programmes suggested by the practical and experienced wire-drawer for (*a*) hard- and (*b*) tough-patented steel wire.

	(*a*)	*Reduction in Area per cent.*	(*b*)	*Reduction in Area per cent.*
1st pass	7 to 8 S.W.G.	17	7 to 8 S.W.G.	17
2nd ,,	8 to $9\frac{1}{4}$,,	24	8 to $9\frac{1}{4}$,,	24
3rd ,,	$9\frac{1}{4}$ to $10\frac{3}{4}$,,	28	$9\frac{1}{4}$ to $10\frac{3}{4}$,,	28
4th ,,	$10\frac{3}{4}$ to $12\frac{1}{2}$,,	32	$10\frac{3}{4}$ to $12\frac{1}{4}$,,	28
5th ,,	$12\frac{1}{2}$ to 14 ,,	33	$12\frac{1}{4}$ to $13\frac{1}{2}$,,	28
6th ,,	14 to $15\frac{1}{2}$,,	28	$13\frac{1}{2}$ to $14\frac{1}{2}$,,	22
7th ,,	..	..	$14\frac{1}{2}$ to $15\frac{1}{2}$,,	20

DRAWING SPEEDS

The speed at which wire is drawn depends on the nature of the material, its size, shape, and the type of machine used. It varies from about 10 feet per minute for thick bars of mild steel from 2 to $3\frac{1}{2}$ inches diameter or smaller bars of high carbon, high speed, and alloy steels to 1000 feet per minute in drawing fine copper wire in continuous machines.

Average speeds for ordinary round mild steel wire are from 50 to 250 feet per minute for rods of about $\frac{1}{2}$ to $\frac{1}{4}$ inch diameter, and from 250 to 600 feet per minute for rods from 5 S.W.G. to 20 S.W.G.

Patented steel wire is drawn a little, but not very much, slower; on the average about 30 per cent. less.

In the matter of speed fairly broad working limits are permissible, particularly in the finer gauges, and much depends on the plant available.

The following typical figures will serve to illustrate the effect of such factors as carbon content and gauge on the speed of drawing wire:

Mild Steel Bright-drawn Bars:

Diameter	*Speed*
$3\frac{1}{2}$ to 2 inches	10 to 15 feet per minute
2 to 1 ,,	15 to 20 ,, ,,
1 to $1\frac{1}{2}$,,	20 to 30 ,, ,,

N.B.—For shapes it is 25 per cent. less.

Round Wire below $\frac{1}{2}$ inch diameter:

Size	*Speed (feet per minute)*	
	0·80 per cent. C.	0·15 per cent. C.
0 S.W.G.	104	115
3 S.W.G.	208	250
7 S.W.G.	250	345

For dead mild steel Atkins has stated values of 400 to 500 feet per minute in drawing a 5-gauge hot-rolled rod to 8 gauge in one pass.

LUBRICATION

It will be readily appreciated that during the drawing operation large frictional forces are at work, and that it is necessary to use a lubricant of some nature to lessen the effect of these forces. Lubricants are essential for two reasons. If they were not used there would be a great possibility of the wire breaking, especially steel wire, because of "binding" in the die, and their help in lessening the frictional forces makes this possibility very much less while at the same time they reduce the load required to draw the material, thereby decreasing the power consumption.

From early records and sketches it would seem that wire was first dry drawn, some kind of grease presumably being used as a lubricant. Later, when the process developed and when power-driven mills were established, it is possible that liquid lubrication was attempted and, presumably, light oils would be tried. Since the unit pressure in a bearing varies from 75,000 to 300,000 lbs. per square inch (33 to 134 tons per square inch) during the drawing of wire and that oil films cannot be maintained above 5000 lbs. per square inch ($2\frac{1}{4}$ tons per square inch) it is not surprising that more efficient lubricants were sought and found in the form of solid bearing emulsions.

It has been long known in practice and confirmed by the research work of several investigators that the most efficient lubrication is obtained with dry soap. The frictional forces are first reduced by coating the steel rod with iron hydroxide, a process carried out after cleaning, or some soft metal such as copper. Thus the steel wire does not actually come in contact with the die itself unless the lubricating film (or sull coat as it is called in the States) and lime impregnated with hard dry soap breaks down as it sometimes does, particularly when the wire has been drawn

many passes or when certain types of continuous machines are used, as has been indicated previously. The truth is that in the drawing of steel wire we are dealing with the laws of dry friction, not of the friction of metal to metal, but of the soap-lime-hydroxide coat on the die.

The forces operating in the wire-drawing die have, during recent years, been the subject of both pure mathematical study and practical investigation by research workers. Most of the conclusions reached have been very clearly summarised in a recent article by K. B. Lewis,[1] from which the following main points arise.

Since wire is deformed in the die it has yielded to the induced forces. It must, therefore, have been stressed to its yield point. It cannot be stressed beyond this point, because immediately it is reached, flow will take place. Hence we have a definite stress as a starting-point. However, this is variable, since the wire is suffering cold work and because of this its yield point will be rising during passage through the die, so an approximation has to be taken.

An approximate estimate of the actual yield point may be obtained as follows. If wire is subjected to too heavy drafting it will break in the throat of the die, or just failing to break, it will "suck down" in diameter, that is it will emerge less in diameter than the hole. It is in effect starting to break, but as it emerges from the die its tenacity increases. The "necking" is transferred back towards the die in a steady progression and the diameter of the entire coil is uniformly smaller than the orifice of the die. If the load which caused this sucking is measured and compared with the breaking strength of the wire twenty-four hours after drawing, when it will have reached a stable condition, it will be found that the yield point at the die exit is about 85 per cent. of the stable breaking strength. This unit stress operates over the area of contact between the wire and the die, but it will be understood better if it is explained in two dimensions. Fig. 17 shows diagrammatically the conditions.

The sum of the forces acting in the die are

$$\frac{(d_1 - d_2)}{2 \sin \theta} p$$

where p is the mean yield point;
d_1 the diameter of the wire at entry;
d_2 the diameter of the wire at exit;
θ the semi-die angle;

but it is only the horizontal component of this force which deforms the wire. This is

$$\frac{(d_1 - d_2)}{2 \sin \theta} p \sin \theta$$

or

$$\frac{(d_1 - d_2)}{2} p \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

It will be seen from the above expression that the angle of the die plays no part in the deformation, thus confirming the previous statements that the angle of the die is of little consequence as far as the material is concerned. However, actual examples calculated on this basis show that the deforming force is considerably less than the measured die pull, in fact, about one-half. The remainder is due to

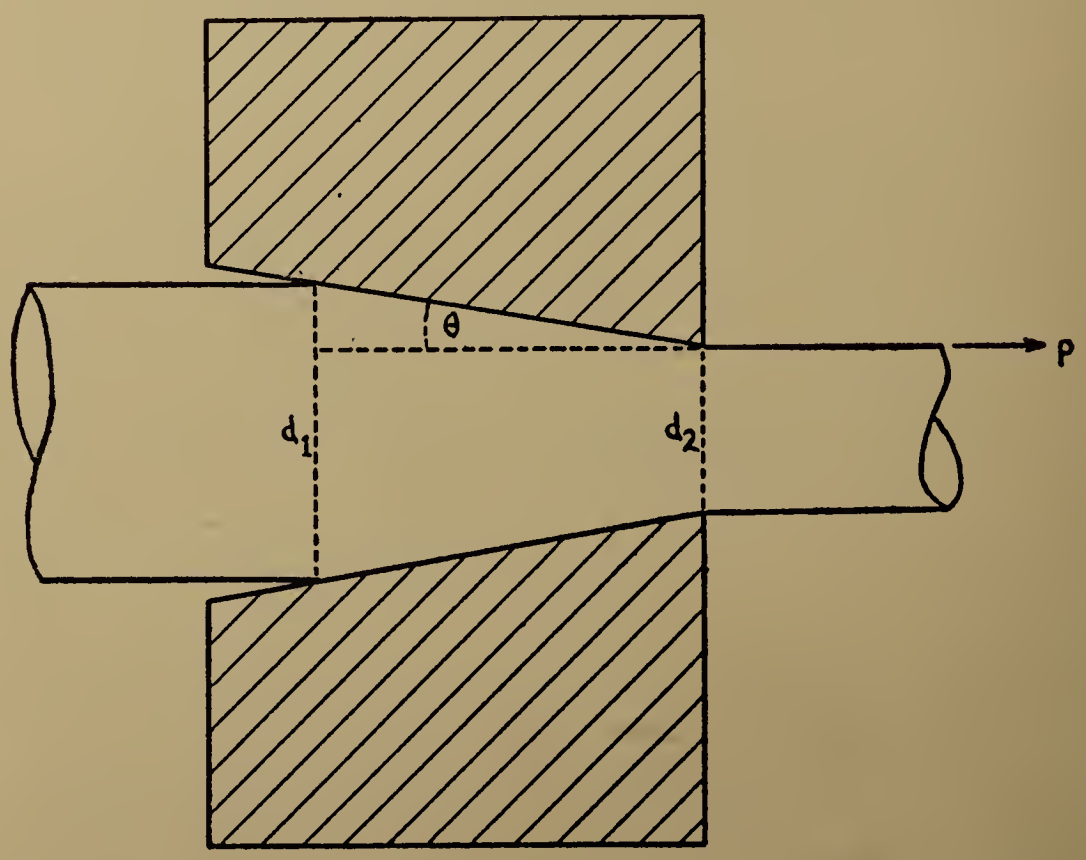


Fig. 17

the frictional forces which are dependent upon the total pressure between the two surfaces and the coefficient of friction.

Hence the total friction is

$$\frac{(d_1 - d_2)}{2 \sin \theta} p.f. \text{ where } f \text{ is the coefficient of friction,}$$

and the horizontal component is

$$\frac{(d_1 - d_2)}{2 \sin \theta} p.f. \cos \theta$$

or

$$\frac{(d_1 - d_2)}{2} p.f. \cot \theta \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Thus the die pull is the sum of (1) and (2)

$$\frac{(d_1 - d_2)}{2}p + \frac{(d - d_2)}{2}p.f. \cot \theta$$

or

$$\frac{(d_1 - d_2)}{2}p(1 + f. \cot \theta) \quad . \quad . \quad . \quad . \quad . \quad (3)$$

The friction factor, $1 + f. \cot \theta$, ranges in numerical values between 1·25 and 3, rising in certain cases to 4 and 5.

In the above formula (3) are two unknowns p and f. Lewis has determined the former experimentally and finds it to be 70,000 lbs. per square inch for mild patented wire. This figure is about the mean between that of the wire entering the die and that leaving the die—*i.e.* about 85 per cent. of the breaking load. Knowing p, f can be calculated and depending upon the die surface, lubrication, etc., works out between 0·065 and 0·110 running close to the figure of 0·085, which is the usual figure in the commercial dry-drawing practice. In wet drawing it usually amounts to 0·13–0·19, figures which might be expected under conditions of scanty lubrication.

Lewis also gives a general law which he had deduced from data gathered over a number of years, and to which the work of all die-makers and wire-drawers conforms within very close limits. There is a constant ratio maintained between the total area of contact and the area of the entering section, and this ratio is 4 to 1. Thus in a light draft the angle must be small to give this ratio and for a large draft the opposite must apply.

It will be seen from what has been written above that lubrication is more efficient in dry than in wet drawing. Thompson [2] gives many interesting figures regarding the relative efficiency of various solid and liquid lubricants and has shown some very interesting facts relating to the effect of heating the liquids. In some cases by heating liquid lubricants their efficiency can be so increased that it equals that of dry soap. This may have a very important and practical bearing, because in many respects wet drawing has distinct advantages in so far as the finished product is concerned. Wet-drawn wire has a finer surface finish than dry-drawn material, and where high polish is essential as in the case of piano wire, the wet process is almost invariably used. During wet drawing the wire is kept cool, and hence it tends to be tougher; moreover, as will be shown later, a highly finished surface free from all irregularities has a profound influence upon the fatigue-resisting properties of the wire. Thus it is not improbable that in spite of the difficulties of lubrication a revival of wet drawing may be within sight.

NATURE OF FLOW IN DRAWING

The flow of a metal in wire-drawing is a matter of supreme importance; it should be, as nearly as possible, uniform throughout the section. The flow of wire

when drawn through a die differs from the flow in extrusion, and also from that obtained by direct strain as in a tensile testing machine.

Under direct tensile strain the greater flow takes place in the core, as may be seen from the structure on a longitudinal section through the waist formed just before fracture on a mild steel rod strained in a tensile testing machine. For the sake of comparison a piece of the same rod may be drawn into wire of the same diameter as the waist, the reduction in both cases being the same, and the structures are strictly comparable. Photomicrographs show that under direct straining the lines of flow are not uniform, the greatest flow being at the core, and in the drawn

Fig. 18

wire the flow is much more nearly uniform, except for a very slight skin effect on the extreme edge.

To analyse the stages of flow under direct tension would be a somewhat complicated matter, but there can be little doubt that the greatest longitudinal flow takes place in the core; the centre crystals are elongated more or less into fibres as in wire-drawing, while the outer crystals are not so greatly elongated. The forces operating under direct tensile loading may be resolved into normal and tangential stresses. Neglecting inter-frictional forces, deformation first takes place by slip or shear on the cleavage planes most suitably situated—*i.e.* those at an angle of 45° to the axis of the test-piece. Thus, in the outer crystals, the deformation in a direction at right angles to the direction of loading will be just as great, if not greater, than in the direction of loading. The crystals in the core, however, are constrained on all sides by the circumferential pressure of the outer crystals, and we get a perfect wire-drawing effect in the core, resulting in extreme elongation of the internal crystals.

In wire-drawing the flow is caused by the combined effect of the direct pull and the circumferential pressure of the die. Thus, when the wire is not too great in diameter, the tendency to greater flow of the centre crystals is just counterbalanced by the greater effect of the die on the outer crystals, and we get uniform flow or elongation of the grains. The larger the diameter of the rod, however, the greater becomes the external flow in comparison with the flow at the core, and the conditions of a thick bar drawn through a die are the reverse of those under direct tensile strain.

In order to show the irregularity of flow in a thick bar the following experiment was carried out at the suggestion of Dr Horsburgh. Several holes were drilled at regular intervals along a $\frac{3}{4}$-inch mild steel bar; these were plugged with $\frac{3}{32}$ inch brass, the plugs being normal to the longitudinal axis. The bar was then drawn

to about ½ inch diameter and sectioned longitudinally to show the new position of the brass plugs. This section is illustrated in Fig. 18. Examination of the etched structure showed greater distortion near the surface, but it is wrong to suppose,

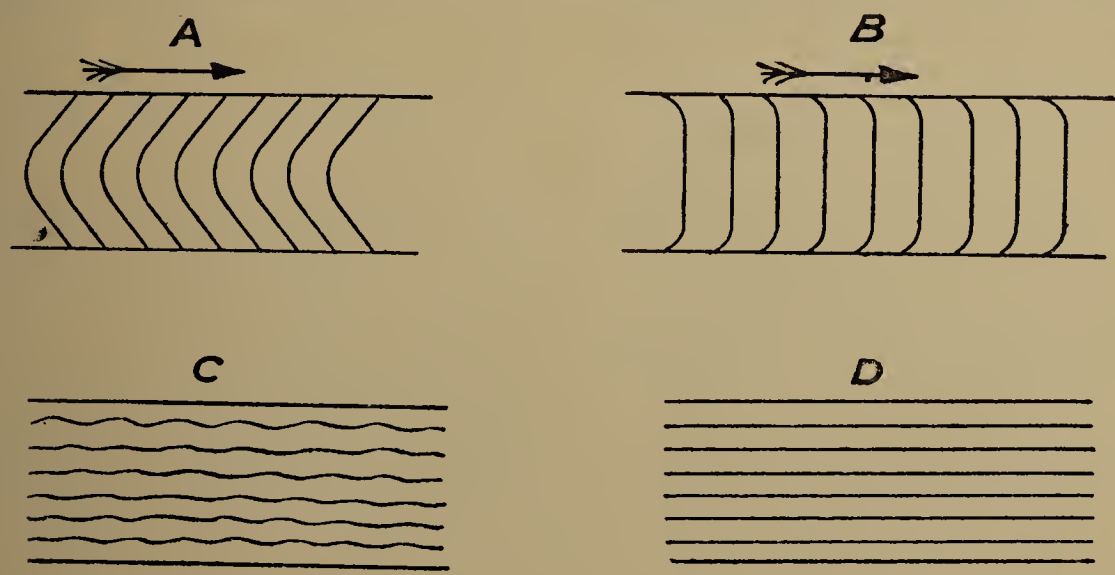


Fig. 19.—*A*, Irregular Flow, leading to Cuppy Wire; Surface Flow greater than Core. *B*, Broken-backed Wire due to Hard or Brittle Skin. *C*, Wavy Flow due to Impurities in the Steel, resulting in Inferior Wire. *D*, Regular Flow, resulting in Perfect Wire

as has been stated, that internal "cupping" produced by the greater flow of the outer crystals is due to the core "lagging behind"; actually, it is the reverse that occurs, the core being pulled through the die without cold flow, and the surface being thrust back by the die; indeed, an actual backward wave may sometimes be detected. This mechanism of flow has been confirmed by Thompson [2] and his co-workers and also by Atkins.[3]

The importance of uniform flow throughout the cross-section of the wire cannot be too strongly emphasised. We shall see later how much this depends on the microstructure and on the homogeneity of the steel, and how closely the physical properties of high tensile wire depend on uniform cold flow in drawing. It only remains here to illustrate diagrammatically typical forms of flow (see Fig. 19).

References

[1] K. B. Lewis, "A Study of Die Stresses and Strains during the Wire-drawing Operation," *Wire and Wire Products*, 1933, vol. viii., July, August, September, and October.

[2] E. L. Francis, "Studies of the Wire-drawing Process," III.—Lubrication, *Iron and Steel Institute, Carnegie Scholarship Memoirs*, vol. xxi., 1932, p. 1.

[3] E. A. Atkins, "The Drawing of Steel Wire and its Relation to Qualities of Steel," *Journal of the Iron and Steel Institute*, 1927, No. 1, p. 443.

CHAPTER IV

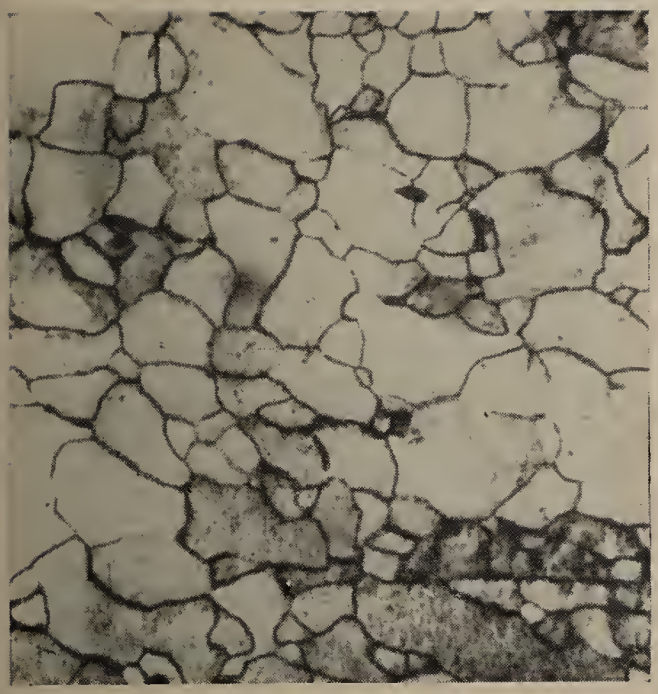
HEAT-TREATMENT

THE heat-treatment of steel in relation to cold work is of such supreme importance that it demands special consideration. Obviously it is beyond the limits of this work to enter into the fundamental principles upon which the heat-treatment of steel is based; and it must be assumed that the reader is sufficiently familiar with the subject, in the general sense, to enable him to pass directly to a consideration of its relation to cold working.

In dealing with this subject we are again bound to divide our material into the two classes mentioned on p. 16. In Class I. the object of heat-treatment is to soften the metal in the first instance, and to remove the hardening effect of cold work, the process used being that of "annealing." Annealing, however, is a term which is used very loosely, and may mean heating the material to any temperature from 100° C. to 1000° C. according to the metal to be annealed and the ideas of the individual in charge of the operation. For pure metals, and most non-ferrous alloys, there is a fairly definite annealing temperature—viz. that temperature at which the rigidity of the metal is sufficiently relaxed to permit the molecules to take up their natural position in the secondary crystalline system—free from internal strain or the effects of previously applied stresses—*i.e.* the temperature of "thermal equilibrium." This temperature differs in each metal. Apart from metals with a low melting-point—such as tin or lead—which are annealed practically at atmospheric temperature, even gold and copper can be annealed at a very low temperature. Thus Beilby [1] found that gold wire could be completely annealed at 280° C. and copper at 250° C. Iron and steel, however, have more than one annealing temperature, because iron is allotropic and can exist in more than one solid form, and because the presence of iron carbide in steel has to be considered in addition to the state of the iron. For this reason the term "annealing" in relation to these metals is generally taken by metallurgists to mean "heating to a temperature just above the upper transformation point, Ac_3, followed by slow cooling through the critical range of temperature." This treatment at the high temperature brings the iron into the γ condition and the carbon into solid solution; and finally, after slow cooling, leaves the iron in the α condition and the carbon as iron carbide.

The term "annealing" is also largely used in the general sense of heating to remove the effects of internal strain, and it is this meaning of the term that is used in cold-working industries. This is natural, since the main object of annealing in these industries is the removal of the effects of previously applied stresses. In dealing with non-ferrous metals such a definition of annealing is usually sufficient,

Plate VII.



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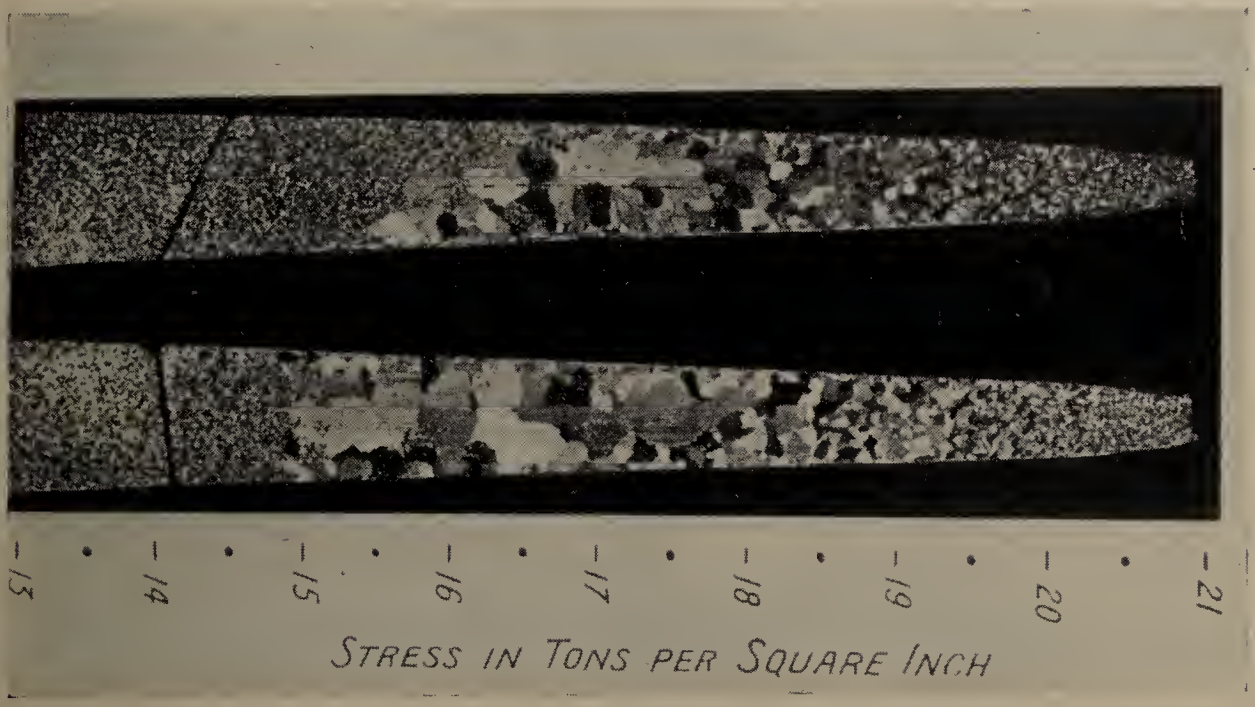

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Fig. 20. IRON WIRE—ANNEALED

Fig. 21. IRON WIRE—HARD DRAWN

Fig. 29. GRAIN GROWTH IN MILD STEEL PRODUCED BY STRAINING AND ANNEALING. Magnified 4.75 Diameters. (*Chappell*)

but in steel and also iron there are certain phenomena connected with cold working and annealing which necessitate special consideration. Although practical experience has, on the whole, taught those engaged in the cold-working trades how to avoid pitfalls, yet occasionally the practical man falls into one, and of course blames the steel. Thus Longmuir [2] was justified in stating:

"A study of current works practice reveals the fact that, generally speaking, annealing operations are considered to have no relation to thermal transformations."

And it is not an uncommon thing to find high carbon steels being annealed one day below the critical range, and the next day above it, with obviously different results.

It may be well here to summarise the more elementary knowledge concerning the microscopical effects of cold working and annealing. Dealing in the first place with iron itself, the effect of wire-drawing, or of pure tension, is to elongate the crystals in the direction of the extension, as is shown in Figs. 20 and 21. The greater the amount of cold work the greater is the extension of the crystals.

On annealing at temperatures below about 520° C., these elongated crystals retain their identity, but at that temperature a complete recrystallisation sets in, and from the large elongated crystals there form an almost innumerable number of new small ones. This is shown in its earliest stages in Fig. 22, where a few of the new crystals are to be seen growing in the old ones. As the temperature is raised the new crystals grow in size and diminish correspondingly in number. Although the old grains still persist up to 520° C. there are slight indications at even lower temperatures that they are becoming unstable, and the etched surface of the metal shows a roughening at still lower temperatures. In skilled hands some suggestion of the temperature to which the cold-worked iron has been raised can be obtained from this effect, though it is at best poor guidance and needs more than a little skill. The appearance of the material annealed at 500° C. after cold work will be obtained from Fig. 23.

Passing on to the corresponding effects in carbon steels, both the ferrite and pearlite are elongated, and again this elongation bears a definite relation to the amount the wire has been drawn. Annealing, so far as the ferrite is concerned, follows very similar lines to those in the pure iron. At 520° C. it recrystallises, and the structure at that point is one consisting of still elongated grains of pearlite embedded in ferrite which has recrystallised and become equiaxed. This is clearly shown in Fig. 24, which is a photomicrograph of a cold-drawn steel tube annealed at 700° C. To remove the elongation of the pearlite, temperatures well above the Ac_1 point of the steel are required, but at around the Ac_3 point the worked structure is entirely eliminated and the normal annealed one takes its place. This is shown in Fig. 25, which is the same material as is shown in Fig. 24, annealed at about 830° C.

There is, however, a very important aspect of the annealing of steels containing pearlite which must be dealt with. In an unworked steel, annealing around 700° C. —*i.e.* at a temperature just below the carbon change point—will, in the course of

time, cause the laminated pearlite to break up and give place to a pearlite in which the carbide is in the form of globules instead of plates. This process is spoken of as the divorce of the pearlite. In annealed material this process is a slow one and may take days to complete itself. Cold working has, however, an important effect in speeding the divorce up, and a cold-drawn wire annealed at 700° C. will lose the whole of its lamination in the course of a comparatively few hours, or even minutes. This is, as will be seen later, a matter of importance in the intermediate annealings of higher carbon steel wires. It may be well to point out that instead of the ordinary etching reagents, picric or nitric acids, which darken pearlite as a whole, etching with a boiling alkaline solution of sodium picrate is often of value, since it darkens only the carbide, leaving the ferrite or the iron matrix of the pearlite light.

Etched with this solution these effects will be well seen from Figs. 26 and 27. Severe hammering distorts the normal laminæ of carbide in unworked steel, as will be seen in Fig. 26, and also probably breaks the brittle carbide plates. Annealing at 660° C. for as short a time as fifteen minutes causes the distorted and broken plates to become almost entirely globular, as Fig. 27 shows. To illustrate the enormous increase in the velocity with which this divorce occurs after cold work, in an unworked steel annealed at 680° C., the degree of globularisation, even after forty hours, is much less complete than is the case with the hammered steel annealed at a temperature of 20° C. lower after only fifteen minutes.

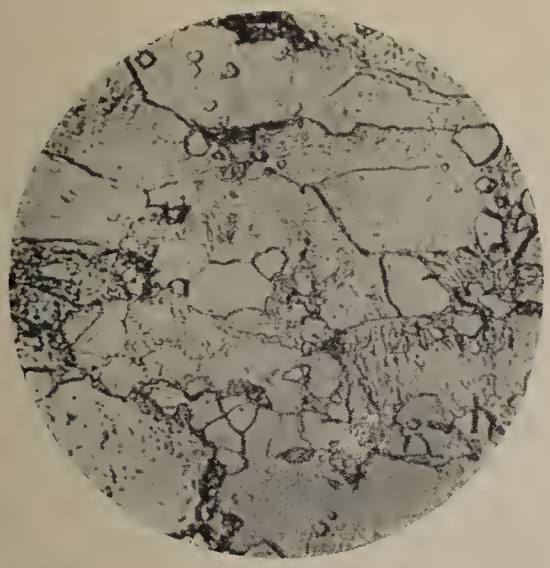
Finally, Fig. 28 shows the complete spheroidalisation in a cold-drawn wire annealed at 700° C. for about an hour and etched this time with picric acid. The whole of the lamination of the carbide, characteristic of the hot-rolled rod, has been completely removed. Material with this structure has a very low elastic limit, and though very ductile and easily deformed is not in a condition suitable for use. It follows, therefore, that such wire, though suitable for further drawing, is not suitable for service, and the treatment for the final annealing must be of a different nature. In general, this final annealing would be carried out at the normalising temperature of the material—*i.e.* at its Ac_3 point. The pearlite, after this treatment, will have been converted into the typical laminated variety characteristic of the initial hot-rolled rod.

The phenomena requiring special attention in annealing iron and steel for cold working are:

(1) The occurrence of grain growth in iron and low carbon steels annealed below the critical range of temperature.
(2) The divorce of pearlite and spheroidising of cementite in high carbon steels at those temperatures.

The former (grain growth) is a thing to be avoided, and the latter a thing to be properly controlled.

It was Stead [3] who first showed in 1898 that strained ferrite, when heated close to, but below, the critical range of the metal, undergoes a marked crystalline growth caused by the adjoining ferrite grains assuming the same crystalline orientation



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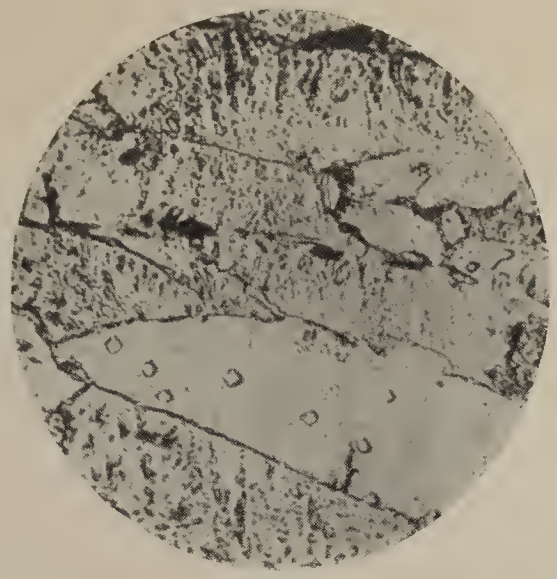

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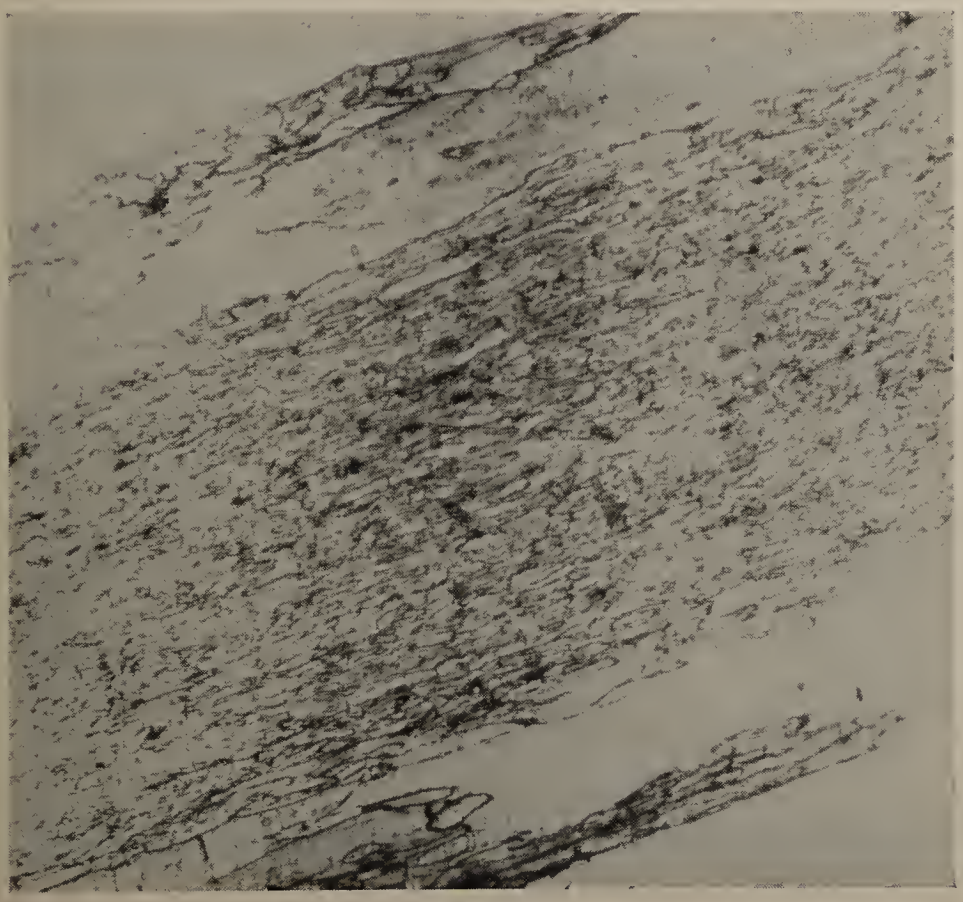

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Fig. 22. IRON ANNEALED AT 571°C. AFTER COLD WORKING. Magnified 700 Diameters and reduced one-third. (*Chappell*)

Fig. 23. IRON ANNEALED AT 500°C. AFTER COLD WORKING. Magnified 700 Diameters and reduced one-third. (*Chappell*)

Fig. 30. GRAIN GROWTH IN ARMCO IRON. Magnified 250 Diameters

and, therefore, merging into a single larger grain. Subsequent investigations by Charpy,[4] le Chatelier,[5] Sauveur,[6] Goerens,[7] Robin,[8] Chappell,[9] and many others have resulted in a more complete understanding of the conditions under which this phenomenal grain growth occurs in iron and mild steel, but the real cause will remain obscure until the entire mechanism of plastic deformation and crystallisation on annealing has been made clear. The facts, as discovered by the above investigators, have been carefully reviewed by Sauveur, and also in a valuable paper by Chappell, in which a detailed study of the crystallisation of deformed iron was made; and it has been established that "the process of crystallisation is one of refinement followed by growth. The extent to which refinement takes place increases proportionally with the degree of plastic deformation. The ultimate crystal size after annealing deformed iron may be regarded as the resultant of these two opposing tendencies, and increases regularly with decrease in the degree of deformation" (Fig. 29). It appears that slight deformation—in rolling or drawing below about 8 per cent. reduction in area—does not produce this abnormal grain growth, because the deformation is not sufficient to induce complete recrystallisation; while severe deformation—above 20 per cent. reduction in rolling or drawing—causes grain refinement. Between these two points, however, as has been shown by experiments on the annealing of iron deformed in the Brinell machine, by bending and direct tensile straining, excessive grain growth occurs at temperatures between 600° C. and 800° C.

When the deformation has been slight only a few of the metal crystals have been affected, and even although recrystallisation occurs at one or two points no growth can take place, because the surrounding crystals are unaffected. When the point of critical strain is reached, however, it appears that all the crystals have been more or less deformed, and when recrystallisation commences at one or two points, where the deformation has been severe, growth is stimulated by the tendency of the first formed crystals to absorb those growing near them. Too many starting-points, however, due to more severe deformation, result in the growth of a larger number of small crystals rather than a few big grains. Thus, whatever the actual cause of recrystallisation on annealing after cold working, the existence of a critical strain may be explained as above.

Robin has put this explanation in different terms by arguing that the straining of ferrite results in the formation of a number of nuclei from which new grains will grow on annealing. When the cold flow has been below the range of critical strain these nuclei are not formed; in critically strained metals a few nuclei are created, giving rise on annealing to a few large grains; while in overstrained metals a great many nuclei, resulting on annealing in the production of a great many smaller grains.

In the same way the presence of sufficient cementite or even non-metallic inclusions effectively prevents the growth of large grains, by providing the nuclei from which a large number of small grains grow.

This phenomenon of grain growth following critical strain is a matter of great

interest, and has been utilised to produce test-pieces of metals in which the entire cross-section consists of one grain only. In this way it has been possible to study many of the properties of single metal crystals, with important results. Apart, however, from this side of the subject, the possibility of accidental grain growth in iron and mild steel, due to annealing below the critical temperature after deformation between 8 and 20 per cent. reduction in area, has to be considered in relation to cold-working operations.

In this chapter we are concerned with it only in relation to the annealing of iron or steel with a carbon content below 0·15 per cent., which may have been critically cold worked by rolling into strip or in drawing bars of special sections.

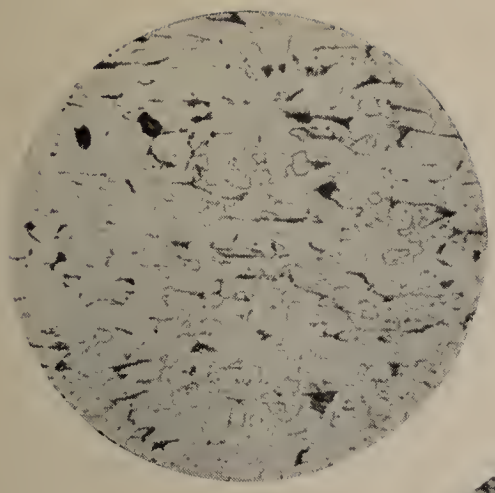
Fortunately the phenomenon of grain growth is rarely encountered under ordinary working conditions in drawing iron or mild steel wire, because the critical cold-working range essential to grain growth is almost invariably surpassed in drawing such wire. It occurs quite frequently in drawing mild steel bright bars, and special shapes also occasionally in cold-rolling operations with disastrous results.

In rolling iron or mild steel strip it sometimes happens that a slight miscalculation is made with regard to the programme or "lay-out" of annealing and rolling stages, and the operator may find himself with a consignment which is just too hard to reduce to the final gauge required. Not having been forewarned of the danger of grain growth he proceeds to have the strip annealed at a temperature of about 650° or 700° C., and then rolls it to the finished size, involving a slight reduction only—say, about 15 per cent. The strip, being required for deep-drawing purposes, has to pass a severe Erichsen or Pittsburg bulge test, and is, therefore, again annealed with the production of huge grains. Under the bulge test complete failure occurs, with the production of "pimples" in the bulge, and unless those in charge are familiar with the phenomenon of grain growth the failure is put down to defective metal. Fig. 30 shows an example of partial grain growth produced by rolling a sample of armco iron within the range of critical deformation, and is particularly interesting, since it shows the enormous difference in size of the crystals produced in this way from the normal size.

Another interesting case of accidental growth is illustrated in Fig. 31. In this case a wire of a special shaped section was produced by drawing, and the annealing also in this instance was accidental, being due to brazing. Further, only the outside of the section is affected, where the steel has been badly decarburised, and the sample illustrates well the fact that when the carbon content of the steel is above a certain point—about 0·15 per cent. according to Sauveur, and generally rather less—grain growth does not occur.

Grain growth is, indeed, very liable to occur in drawing mild steel in intricate sections, because the degree of deformation between each annealing is necessarily much less than in drawing round wire, and is also bound to vary, to some extent, in different parts of the section. Therefore the final annealing operation in such material, when the carbon content is low, should always be conducted above the upper transformation point, Ac_3—*i.e.* about 850° C.

Plate IX.



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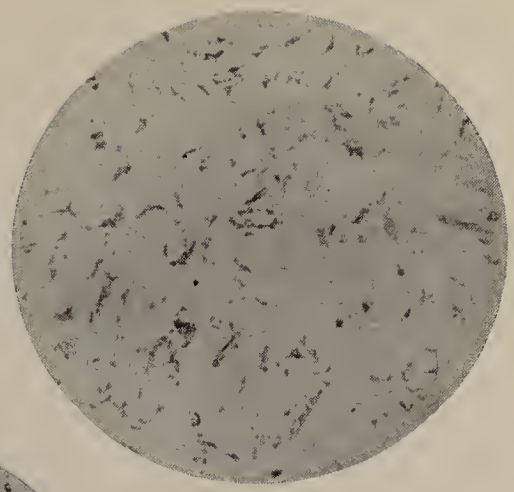

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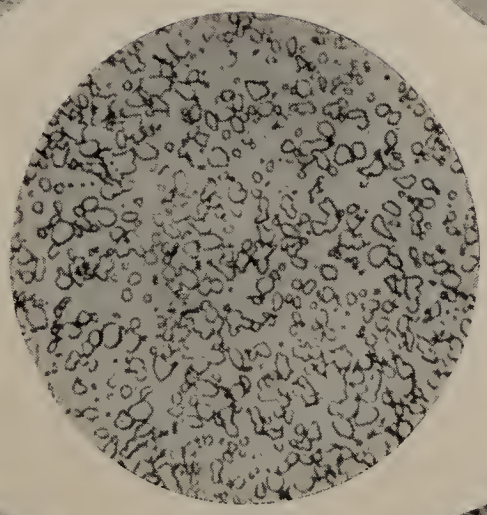

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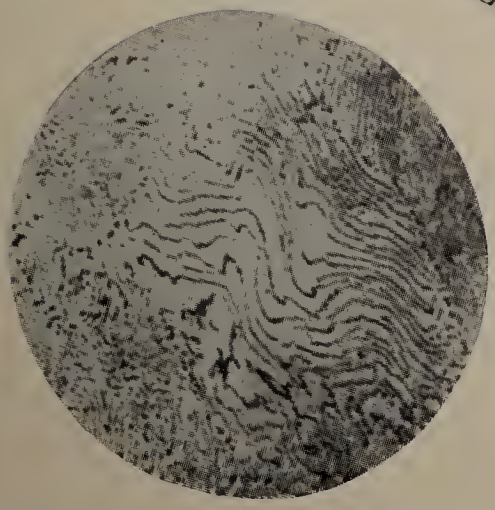

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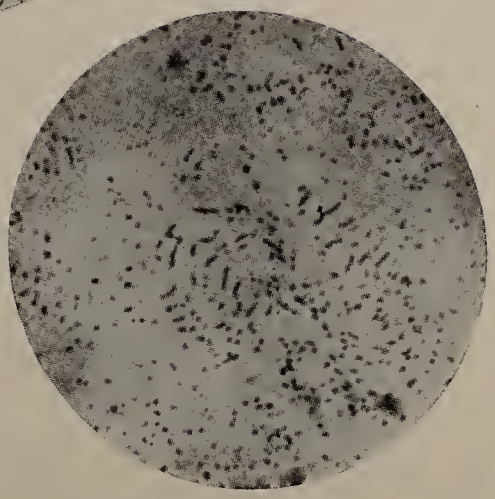

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Fig. 24. COLD DRAWN MILD STEEL TUBE ANNEALED AT 700°C. THE FERRITE HAS RECRYSTALLISED, BUT THE PEARLITE IS STILL ELONGATED. Magnified 100 Diameters. (*Thompson*)

Fig. 25. COLD DRAWN MILD STEEL TUBE ANNEALED AT 830°C. THE PEARLITE IS NO LONGER ELONGATED. Magnified 100 Diameters. (*Thompson*)

Fig. 26. LAMINATED PEARLITE DISTORTED BY SEVERE HAMMERING. ETCHED WITH SODIUM PICRATE. (*Whiteley*)

Fig. 27. DISTORTED PEARLITE ANNEALED AT 660°C. FOR FIFTEEN MINUTES. ETCHED WITH SODIUM PICRATE. (*Whiteley*)

Fig. 28. SPHEROIDAL CARBIDE IN COLD WORKED WIRE AFTER ANNEALING AT 700°C. ETCHED WITH PICRIC ACID. (*Thompson*)

The other phenomenon—viz. spheroidalisation of the pearlite—is one of which the trade has unconsciously taken advantage; but it may be stated here that what is of advantage for cold working is not always so for subsequent operations. In drawing or rolling steels of a refractory nature, such as high carbon steels for needles, drill rods, dental instruments, etc., or such alloys as high-speed steel which are destined ultimately to be hardened and tempered, the object is to get the steel into the softest and most ductile condition possible, and the annealing operations have to be considered from two points of view:

(1) The preliminary annealing of the hot-rolled material, which may in the first instance be in the nature of a heat-treatment for homogeneity, and in the second such as to obtain maximum initial ductility.
(2) The intermediate annealings in the various stages of cold work, which must aim at maximum ductility.

It is frequently the case that the preliminary annealing gives most trouble, and the reason, briefly stated, is that there is difficulty in getting the steel into its most ductile condition before it has received any cold work. Thus, paradoxical as it may seem, cold working is an indirect method of ultimately softening steel. In the naturally annealed state such steels as we are discussing consist structurally of finely laminated pearlite and free cementite, and, as will be seen later, a structure consisting entirely of laminated pearlite is quite unsuitable for withstanding cold work. When, in addition to laminated pearlite, we have a network of comparatively thick bands of cementite, it will be obvious that the resistance to cold flow is greatly increased, and it is almost essential to break down this structure in some way before commencing cold-working operations. The best way of doing so is to cause the divorce of pearlite and the spheroidising of cementite. This forms the subject-matter of two papers: "Damascene Steel," by Belaiew, *Journal of the Iron and Steel Institute*, 1918, No. 1, p. 417; and "The Effect of Cold Work on the Divorce of Pearlite," by Whiteley, *Journal of the Iron and Steel Institute*, p. 353. Belaiew's work describes how, in the production of Damascene steel, the structure obtained by continual forging below the critical temperature range produced in the steel the globular or spheroidal cementite, which is one essential feature of the Damascene steels. Whiteley demonstrates how the breaking up of the laminations of pearlite is rapidly accomplished by annealing after cold work. Since this is the structure desired in order to make high carbon steels and alloys, such as high-speed steel, ductile for cold working, the proper treatment for these steels is indicated. In the first instance, before the steel has been cold worked at all, prolonged annealing below the critical range would be required to bring it into this condition. Since such annealing is costly, however, the steel must be given a very light pass while still in the laminated condition, or the final passes in hot rolling the rod may be carried out below the critical range. The conditions will then be somewhat similar to those mentioned by Belaiew as essential in producing the Damascene structure. Once the difficulties of the preliminary annealing and the first pass are surmounted,

the subsequent treatment is simple, the wire being annealed at a temperature ranging between 650° C. and 700° C.—*i.e.* below the A1 point. This treatment not only keeps the wire in its most ductile condition for drawing, but leaves it finally in its softest condition for subsequent wire-forming—a factor of great importance. In some instances, however, the spheroidised cementite and divorced pearlite structure is undesirable in the finished wire. In the higher carbon steel wires it is sometimes found that the requisite temper is not obtained by the ordinary hardening treatment. Before hardening such wire the author sometimes finds it necessary, in the first place, to remove the globular structure by heating the steel above the cementite change-point, so restoring the strengthening network of free cementite. This preliminary treatment also reduces any tendency to warp in hardening.

The structures referred to in the text are well illustrated in the above-mentioned papers, and the photomicrographs in Figs. 26 and 27 are reproduced from Whiteley's.

From a consideration of the above we may now summarise the important points in regard to the heat-treatment or annealing of high carbon and alloy steel wire for subsequent hardening and tempering:

(1) Since such steel must be considered refractory in regard to cold-working operations it is important not only that it should be free from all defects of composition, etc., but that it should be as nearly homogeneous as possible. Steel of this type, however, is generally cast in small ingots, and there is not the same danger of heterogeneity as in ordinary steels.

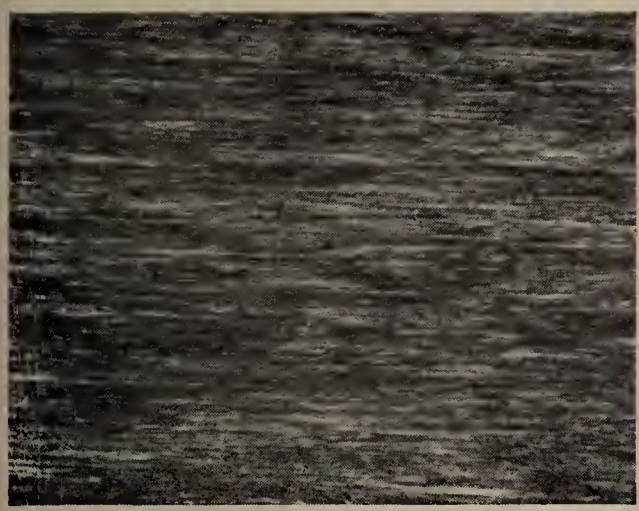
(2) The preliminary annealing of the wire steel should consist of a thorough soaking between 650° C. and 700° C. In this way, at least, a partial breakdown of the laminated pearlite and cementite network may be effected, which will be more complete if the final passes in hot rolling have been conducted below the critical range of temperature.

(3) Since the preliminary annealing may not produce the desired effect on the structure, the first pass in drawing should be a light one.

(4) In subsequent annealings between each stage in drawing there is no longer the same necessity for prolonged soaking, since the cold work greatly assists the separation of the constituents into globular carbide and free ferrite. The best results, however, are obtained by soaking in a pot for several hours at a temperature between 650° C. and 700° C., or, in the case of high speed steel, 700° C. to 750° C.

One very important point to be observed in connection with all annealing operations on steel for hardening and tempering is the prevention of scaling and decarburisation, since, in many cases, hardness on the surface of the material is even more important than in the interior. Wherever possible the decarburised surface should be removed by grinding. Carbon steel drill rods, etc., which are delivered in straight lengths are now ground in centreless grinding machines.

Plate X.



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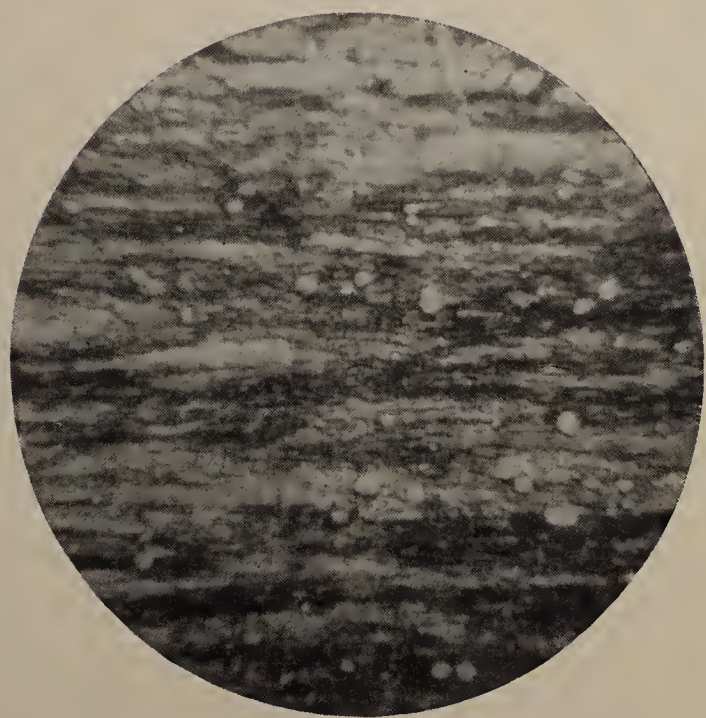

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Fig. 34. LONG FIBRE WIRE—RESULTING FROM HIGH PATENTING TEMPERATURE. Magnified 130 Diameters

Fig. 35. SHORT FIBRE WIRE—RESULTING FROM LOW PATENTING TEMPERATURE. Magnified 130 Diameters

Fig. 31. ACCIDENTAL GRAIN GROWTH IN A SHAPE WIRE

Fig. 33. GLOBULAR CEMENTITE IN HYPO—EUTECTOID STEEL, DUE TO PATENTING AT TOO LOW A TEMPERATURE

ANNEALING OF MILD STEEL WIRE

The annealing of mild steel or iron wire presents little difficulty.

Wire of this class is usually annealed in coils on an open pan, if the furnace is so designed that excessive oxidation is avoided. It may also be annealed continuously by passing the wire through a long furnace. This latter process, which is frequently adopted in finally removing the effects of cold working before hot galvanising of telegraph, fencing, and barbed wire, etc., is sometimes erroneously termed "Patenting"; but this term should be applied only to the heat-treatment of high tensile wire, to be described later.

The temperatures reached in annealing mild steel wire may vary considerably without causing trouble, but there is really no necessity to go much beyond 600° C. or 700° C., since the chief effects of cold working in mild steel wire are virtually removed at a temperature of about 550° C. This has been definitely shown by Goerens.[7] It is well to remember, however, that there is one effect of cold work which remains—viz. the gradual decrease in grain size—and, as will be seen later, a fairly large grain is desirable in cold-working operations. Also the globular structure which results is often undesirable, even in mild steels, and should be removed. It is therefore sometimes advisable to anneal even mild steel wire at a temperature of about 900° C.

HEAT-TREATMENT OF HIGH TENSILE WIRE

High tensile wire receives a special form of heat-treatment. The process known to the trade as "Patenting" is not a true annealing, nor even a normalising, as has often been assumed. Bedson [10] states that it was first used by Mr William Smith of Warrington, but this does not appear to be correct, as shown by the following account supplied by Mr Luckman of Messrs Latch & Batchelor, to whom the author is indebted:

"The process was invented by James Horsfall of Birmingham, who was granted Royal Letters Patent for his invention in 1854. It was due to this that the term 'Patenting' became associated with the process, and the wire produced by that method was known as 'Patent steel.'

"James Horsfall entered partnership with Baron Webster of Penns, and the two carried on business at Penns & Hay Mills, under the name of 'Webster & Horsfall.'

"The firm supplied wire to John Fowler of Leeds, and to meet the requirements of steam ploughing introduced a hard grade of patent steel, which was known as 'Patent plough'; afterwards, as tensiles increased, 'Improved plough and extra plough' followed.

"The William Smith referred to above was originally in the employ of Webster & Horsfall, but left their service, and after being for a time associated with Abel

Rollason commenced drawing wire in two cottages at Warrington. The business grew, and after securing the services of another employee of Webster & Horsfall as foreman, commenced heat-treating wire in a way that James Horsfall considered was an infringement on his patent.

"A law suit followed, but the verdict went against Horsfall, for although the object aimed at was the same, the operation was entirely different.

"The process employed by Smith was to wind the wire on to a block in an oven, bring it to the required temperature, then wind it back into the air. Horsfall's patent was for the present type of muffle, with metal bath."

Although this form of heat-treatment seems to be used exclusively in the wire industry there is little doubt that some modification of it might find useful applications in other steel products. The development of metallography has shown us now, what was naturally unknown to the originators, that the main object of the process is to bring the steel into the sorbitic condition. It is almost invariably a continuous process, the coils being placed on swifts at one end of a long furnace and pulled through, in the first instance, by "leaders" attached to the winding machines at the exit end. The length of the furnace and the speed of travel are so arranged that the wire is sufficiently long in the furnace to reach the required temperature. Naturally, the hottest end of the furnace is the exit end, since the wires carry the heat to this end. Thus the wires are gradually heated to the maximum temperature before cooling commences, the recalescence on cooling occurring about 2 or 3 feet beyond the exit. The furnace used is of the muffle type, the heating chamber being divided into a number of tubes. In the older types coal firing was used, but heating by producer gas is now usual. Electrically heated patenting furnaces are now in use and there will doubtless be developments in this type of furnace in future. In the United States heating by town gas is now common and it is then unnecessary to use the muffle type of furnace, the wires passing directly through the combustion chamber with the advantage of considerable reduction in the amount of scale produced.

The objects of the patenting process are:

(1) General normalising of the steel; removal of rolling stresses and of differences in structure, which inevitably exist from the point to the back end of a long coil; and, to some extent at least, the improvement in homogeneity obtained by solid diffusion at a high temperature.

(2) The production controlled by the rate of cooling of the particular structure —viz. large crystal size and sorbitic pearlite—required for cold drawing.

Many experiments with different steels were carried out by the author to find the best patenting temperature, but it will be sufficient, by way of illustration, to give the results of one experiment only. These are given in graphical form in Fig. 32. This shows the effect of patenting a medium carbon steel at 850° C., 950° C., and 1050° C. respectively on the maximum stress, reduction of area at fracture, and torsions at each stage in drawing.

At first sight it may appear that there is very little difference in the results, and this indeed was stated in the original report:

"The effect of temperature variation between 850° C. and 1050° C. is not very striking, but the results appear to indicate that the capacity to stand cold work increases with the temperature. . . . The differences due to temperature, however,

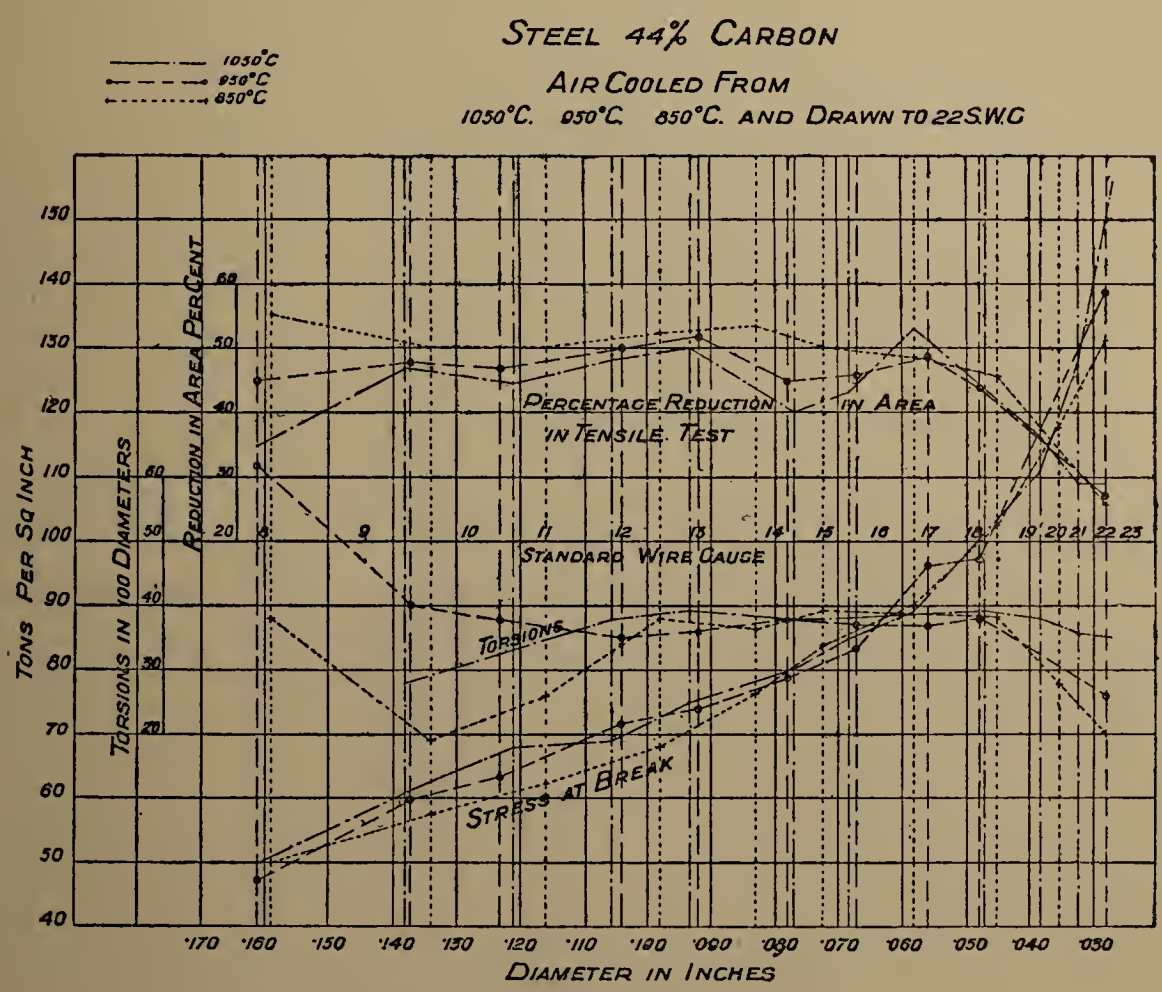


FIG. 32

are so slight we may conclude that the safe working range of temperature in the patenting process is extremely wide."

Slight as the effect of patenting temperature is, however, there is one particularly important point brought out by these results—viz. that all traces of brittleness due to "ingotism" or overheating, although evident in the rod as patented at 950° C. and 1050° C., appear to be removed after a single pass in drawing, and are certainly obliterated entirely after 4 passes. This is made particularly evident by the curves of percentage reduction in area. The importance of this fact, which has been fully confirmed by numerous experiments, is that all the benefits of heat-treatment at a high temperature can be obtained without the disadvantages which prohibit it in ordinary normalising. In ordinary heat-treatment the metallurgist has to employ the skill and care of the chef, since the meat must neither be over- nor

underdone, but the wire-drawer is not an epicure and so long as the joint is *not* underdone he will stand a good deal in the way of overcooking. This simplifies greatly the patenting process, especially since there are one or two practical considerations which would make the control of temperature within very fine limits rather troublesome. The process is almost invariably a continuous one and quenching occurs on a falling temperature, involving a slight loss of heat between the end of the furnace and the quenching bath. This does not matter when the temperature at the exit of the furnace is well above the critical point. Again the continual passage of cold wire through a long furnace, dragging the heat with it to the exit of the furnace, and out of it into the air or the quenching bath, would make extremely accurate temperature control more difficult. Finally, time is necessary to ensure complete solution of ferrite and iron carbide, and this progresses more rapidly as the temperature rises. Comparatively large globules of free cementite are sometimes formed in the rod or wire by preliminary cold working of "ripping," followed by the annealing below the critical range which is inevitable in the gradual heating up of the wire as it travels through the furnace, and a final temperature well above the upper critical point is necessary to ensure the complete solution of these globules. That they can exist even in hypo-eutectoid steel is evident from the photomicrograph in Fig. 33.

For the foregoing reasons alone, it is fortunate that temperatures in the neighbourhood of 1000° C. can safely be employed in the patenting process.

Previously, the author suggested that the coarse-grained structure produced by heating to temperatures between 1000° C. and 1100° C. gave the steel greater ductility in the sense of giving it greater capacity for withstanding cold flow and producing wire with a long fibrous structure. Too much perhaps has been made of this question of grain size, more certainly than was intended when it was first pointed out that grain refining was emphatically not one of the objects of patenting. The point is that while the large austenitic grains produced may not afford the real explanation of the value of a high patenting temperature, they are at least not detrimental as in ordinary normalising.

As Robertson has shown [11] it is almost impossible to determine what constitutes a true crystalline grain in the sorbitic structure of patented wires. In steels containing 0·35 per cent. carbon, the original austenitic grains are outlined by ferritic envelopes, but in higher carbon steels free ferrite is absent and the only structure visible at low magnification is that due to different orientations of pearlite, as may be seen from Fig. 38. This difference in orientation appears to explain the typical black-and-white fibre of the hard-drawn wire as illustrated in Figs. 34 and 35. Whether the actual length of fibre is determined by differently oriented pearlite areas or by the original austenitic grains appears uncertain, but it seems probable that the latter is the real factor since long fibre wire, typically illustrated in Fig. 34, and the short fibre in Fig. 35 are produced mainly by high and low patenting temperatures respectively, though it is true other factors such as the system of draughting have some bearing on the matter.

Since the patenting temperature does not appear to influence the pearlite orientations in any well-defined or consistent manner, it would appear that the fibre length of the finished wire is largely determined by the size of the original austenitic grains. Even if this be so, however, it does not necessarily follow that this is the primary reason, or even a reason at all, for the use of high patenting temperatures. It may be that large grains and long fibres are purely incidental effects. It is certainly true that a large grain structure is capable of greater elongation. This is fairly obvious from purely theoretical grounds. In pure metals and simple alloys especially does it apply, since the gliding planes will naturally be in similar directions in any one grain, and the fewer grains the more uniform the flow, the ideal structure for flow being one in which the centre cross-section consisted of a single grain.

That the ductility of a metal does increase with the grain size is shown by experiments carried out by Carpenter and Elam [12] on aluminium. From their results the following figures are taken:

No. of Crystals in Test-piece	*Maximum Stress Tons per sq. in.*	*Elongation per cent.*
1	3·2	61
2	3·1	51
3	3·2	45
150	4·6	37

Subsequent results obtained on iron test-pieces fully confirm the above conclusion.

Carpenter and Robertson [13] have shown in great detail the extraordinary variety of structures which may be obtained on heating and cooling hypo-eutectoid steels, and a study of their work will afford a partial explanation of the value of patenting temperatures at least beyond 900° C. The structures illustrated in their paper have been found in practice, but they are not frequently encountered in patented wire, or at least should not be. For this there are two reasons. In general the manganese contents of steels used in practice are higher than those of the steels used in the above-mentioned paper, and the influence of this element on the structural changes involved is profound. Moreover, patenting temperatures are nearly always at least high enough to avoid the formation of such structures typified by Fig. 47, which are undoubtedly bad from a wire-drawing point of view, because the proportion of free ferrite is excessive. The real explanation of the value of high patenting temperatures does not lie entirely, as has been suggested—though not by the above authors themselves—in the greater homogeneity obtained by the lesser ferrite deposition at the boundaries of the larger austenitic grains. This explanation is, of course, partly true, but it does not explain the case of a eutectoid steel where no free ferrite is deposited, nor does it explain the difference between wires patented at 950° C. and 1050° C.

The fact remains, although it is not of supreme practical importance, that a wire patented at 1050° C. has a greater capacity for cold flow than the same wire

patented at 950° C. This is clearly illustrated by curves (1) and (2) in Fig. 50. Obviously the short fibre wire of curve (1) may be just as satisfactory and for some purposes possibly more satisfactory than the long fibre wire of curve (2), but the point made here is that the larger austenitic grain obtained at 1050° C. has enabled the wire to be drawn farther without excessive hardening. It should be added, however, that though the grain size appears to influence the capacity for drawing in patented steel wire, it does not appear to do so to the same extent in very ductile metals. In very pure metals such as gold the wire can be drawn far beyond the limits recognisable by fibre length.

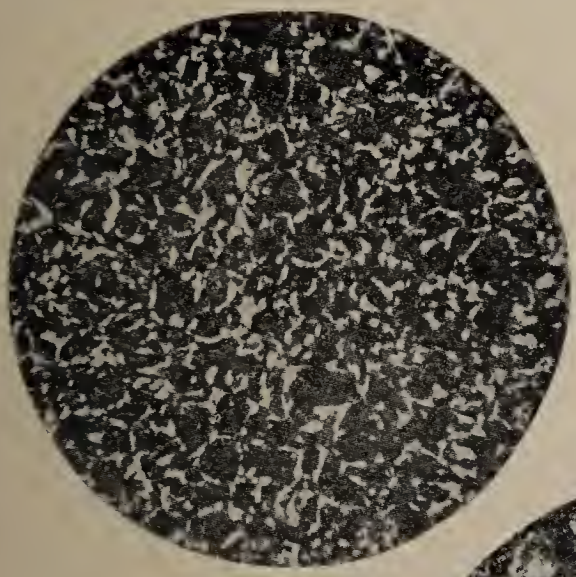
Although the question of grain size and fibre length has been discussed at some length above, its importance should not be over-emphasised. The points of interest related to it are that what would normally be overheated steel makes good wire when drawn far enough, and that the patenting temperatures should be governed by the percentage reduction in area the wire is to receive, the practical range being between 900° C. and 1050° C.

It has been suggested that the McQuaid-Ehn test for grain size might find useful application in determining the suitability of a steel for patenting and wire-drawing.

Briefly this test consists in carburising the steel under standardised conditions so that it becomes hyper-eutectoid on the skin, and the grain boundaries are then clearly marked by the cementite envelope. The sample so treated is then compared with standards. The author has applied this test to steels of various compositions selected at random, but so far has been unable to find any appreciable difference. The test is used to detect abnormality in a steel, however, and its usefulness would much depend on the frequency with which abnormal steels were likely to be met from a particular source of supply. Whether it is a test which may become part of the routine inspection of steel for wire-drawing, or remain in the background as a "pathological" test in the case of a particular steel giving trouble, will depend on individual experience.

Of much greater importance than grain size is the structure determined by the rate of cooling from the patenting temperature. When steel of the dimensions of wire rods is cooled freely in air the particular variety of finely laminated pearlite obtained is fortunately well suited for cold working. But more accurate control of this can be obtained by quenching at a particular temperature. Exhaustive research into this question has been made by Robertson [11] and others. Of the many varieties of structure and texture of the micro-constituents obtained by the transition from austenite on cooling in different quenching mediums only the constituent conveniently termed sorbite, which results from the rapid transition at temperatures in the neighbourhood of 500° C., is apparently of practical importance in the treatment of wire.

At high temperatures cooling is slower and thick plates of cementite have time to form, giving structures of the more or less laminated variety of pearlite which, as will be shown later, are not suitable for cold drawing. At lower temperatures



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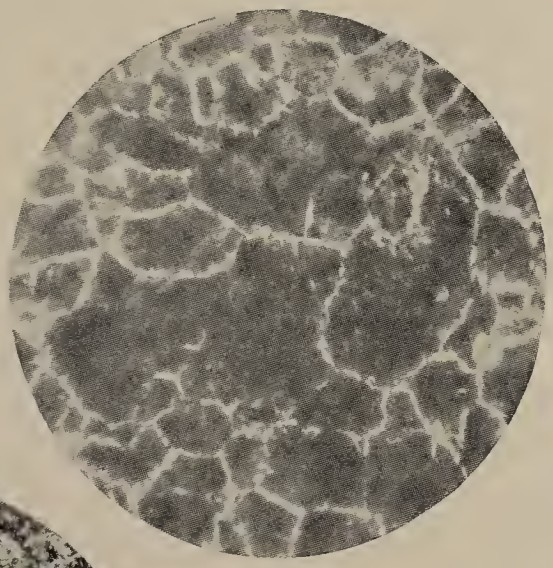

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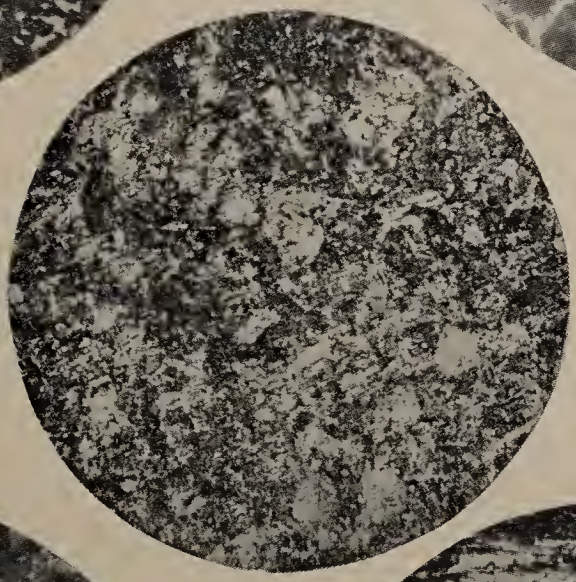

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Fig. 36. 0.50 PER CENT. CARBON STEEL. HOT ROLLED ROD. Magnified 150 Diameters

Fig. 37. 0.50 PER CENT. CARBON STEEL. PATENTED AT 1,000°C. AND AIR COOLED. Magnified 150 Diameters

Fig. 38. 0.50 PER CENT. CARBON STEEL. PATENTED AT 900°C. AND LEAD COOLED. Magnified 150 Diameters

Fig. 39. 0.44 PER CENT. CARBON STEEL WIRE DRAWN 1 PASS AFTER PATENTING. Magnified 250 Diameters

Fig. 40. 0.44 PER CENT. CARBON STEEL WIRE DRAWN 4 PASSES. Magnified 250 Diameters

the speed of transition from austenite becomes progressively slower until a temperature of 250° C., is reached, but the subsequent cooling to normal temperatures of this partially retained austenite results in the formation of troostite and martensite, both of which constituents lack the necessary ductility for wire-drawing.

The possibility of delaying the austenite-martensite transition by quenching at 250° C., clearly demonstrated by Dartry Lewis,[14] is extremely interesting, and possibly some practical use of this phenomenon may be made in certain directions.

It might have had useful application in the wire industry, since austenite is extremely ductile. Unfortunately, cold working itself initiates the transition to martensite, which is anything but ductile.

The complete study of the transition stages from austenite to pearlite, sorbite, troostite, and martensite is intensely interesting, but since it lies somewhat beyond the scope of a text-book on wire-drawing those interested are referred to the original work on the subject.

The capacity of a metal for withstanding plastic deformation, such as is involved in wire-drawing, depends on a great many different factors, and in medium or high carbon steels not the least important of these is the microstructure. Evidence of this is to be found in the following simple example.

A coil of steel wire, No. 8 S.W.G., or 0·160 inch diameter, and of the following composition:

Carbon	0·85 per cent.
Silicon.	0·12 ,,
Manganese	0·30 ,,
Sulphur	0·022 ,,
Phosphorus	0·020 ,,

was selected, and two pieces of this coil were treated as follows:

(1) Annealed by heating to 900° C. and cooling slowly in the furnace.
(2) Patented by heating to 1050° C. and cooling in lead at 600° C.

Sample (1), after annealing, had a maximum stress of about 40 tons per square inch; a good general elongation over a length of 8 inches, but a comparatively poor local elongation at the point of fracture, the percentage reduction in area at fracture being practically nil. This wire was then drawn in the first pass to 9 S.W.G., and in the second pass to 10 S.W.G., at which point it broke in drawing, and continued to break after repeated attempts to draw it farther. Annealed wire can, of course, be drawn a great deal farther than this, if the reduction at each pass is very slight —for example, Longmuir [2] succeeded in drawing a steel containing 0·89 per cent. C. from 0·212 inch diameter rod to 0·072 inch diameter wire without intermediate annealing by reducing it only one-thousandth of an inch at each pass; but, as he states himself, this does not represent commercial conditions of drawing, the reductions per pass being very slight.

Sample (2), after patenting, had a maximum stress of 75 tons per square inch; a good local elongation of about 20 per cent., on a $\frac{1}{2}$-inch gauge length; a reduction in area at fracture of 24 per cent.; and stood, on an average, 10 torsions in a length equal to 100 diameters.

This wire was then drawn 8 passes with an average reduction in area of 20 per cent. at each pass to $17\frac{1}{4}$ S.W.G., or 0·054 inch diameter without breaking.

The behaviour of these two samples clearly shows that, under practical working conditions, steel of this composition in the annealed state is very much inferior as regards its capacity for drawing out as in a wire to the same steel in the patented state. Thus the latter, although much harder, is also much more ductile—a state of affairs that can only be fully understood by examination of the microstructures.

The above example makes it clear at the outset that the heat-treatment of high tensile wire is not a softening process, but rather a toughening process, the object being twofold:

(1) To obtain ductility in the sense not of ease in drawing so much as greatest capacity for uniform cold flow.
(2) To obtain the greatest initial strength in the wire prior to drawing, consistent with the necessary ductility.

The reason why laminated pearlite, although softer than sorbitic pearlite, is less suited for wire-drawing is clearly illustrated in Fig. 45. This is a longitudinal section of wire containing 0·80 per cent. C. which has been drawn 2 passes after annealing. In some grains the laminations are directly opposed to the direction of drawing, in others they are more favourably situated; hence irregular flow takes place, resulting before long in fracture.

The structure obtained by patenting—conveniently termed sorbitic—on the other hand is so finely divided that it can hardly be resolved by the highest powers of the microscope. The author has previously referred to this structure as granular; and although some investigators have insisted that it is not really so, but very finely laminated, and is therefore merely a form of pearlite, the photomicrograph in Fig. 44 hardly supports this view. Whether one calls the structure sorbite or merely a form of pearlite has, however, no bearing on the practical aspect of the matter, since pearlite or sorbite is after all only a secondary constituent, being an aggregate, variable in composition and texture of the two primary constituents—ferrite and cementite. Sorbitic pearlite, then, being more nearly, if not entirely, granular, can flow equally well in all directions. The flow of sorbite is, in fact, more uniform than even that of ferrite, and still more uniform than the duplex structure of ferrite and pearlite.

This is illustrated by the following experiment on thick bars, where the effects of irregular flow are particularly emphasised.

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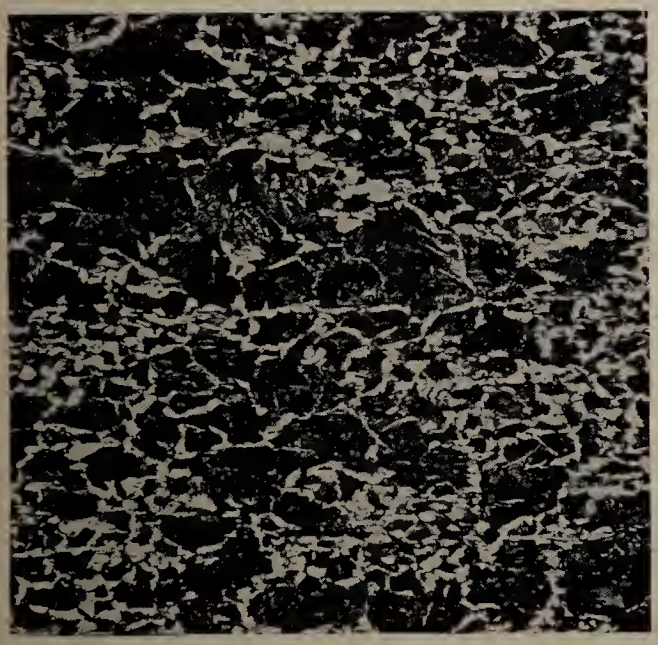

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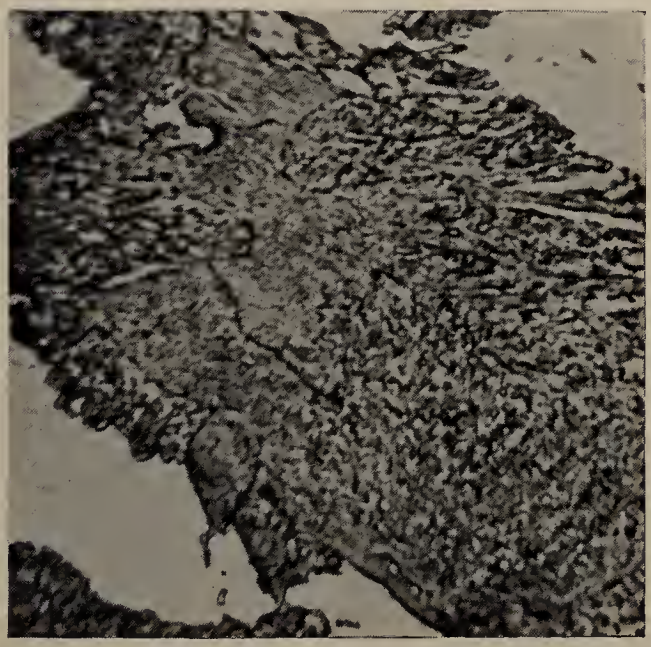

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Fig. 41. 0.45 PER CENT. CARBON STEEL PATENTED AT 1,000°C. AND AIR COOLED. Magnified 200 Diameters

Fig. 42. 0.45 PER CENT. CARBON STEEL PATENTED AT 1,000°C. AND AIR COOLED. Magnified 2,500 Diameters

Fig. 43. 0.35 PER CENT. CARBON STEEL PATENTED AT 1,000°C. AND LEAD COOLED. Magnified 200 Diameters

Fig. 44. 0.35 PER CENT. CARBON STEEL PATENTED AT 1,000°C. AND LEAD COOLED. Magnified 2,500 Diameters

A bar, $1\frac{1}{4}$ inches in diameter, of acid open-hearth steel of the following composition:

Carbon	0·49	per cent.
Silicon	0·13	,,
Manganese	0·65	,,
Sulphur	0·037	,,
Phosphorus	0·039	,,

was divided into two parts, (*a*) and (*b*).

(*a*) Was annealed at 900° C. (Microstructure similar to Fig. 45, save that about half the area was free ferrite.)

(*b*) Was patented at the same temperature, Fig. 44.

The first piece was drawn to a bar $\frac{13}{16}$ inch in diameter, when it broke with a "cuppy" fracture. The second piece was drawn to about $\frac{9}{16}$ inch in diameter without fracture—that is, a reduction in area of 79 per cent. against 55 per cent. in the case of the annealed bar.

A comparison between the behaviour of these samples with the flow of a mild steel drawn by Goerens may be of interest, as it clearly shows that sorbitic pearlite flows even more freely than free ferrite.

Goerens found that a bar of rolled iron 15 mm. in diameter—that is, half the diameter of the author's sample, and therefore, from the point of view of size much easier to deal with—when drawn down to 9 mm. was completely cupped internally.

Goerens carried out many other experiments on drawing, and his report "On the Influence of Cold Work and Annealing on the Properties of Iron and Steel" is of great value; but in dealing with medium and high carbon steels he evidently used annealing instead of patenting as his initial heat-treatment. His conclusion, therefore, that

> "the extent to which deformation may be carried at ordinary temperatures diminishes . . . as the carbon content is increased"

is quite erroneous from the practical point of view, because he was comparing the flow of free ferrite with laminated pearlite instead of with sorbite.

The above are examples of extreme differences in the structure of the pearlite constituent, but they serve to emphasise and to explain the minor differences due to varying the rate of cooling from the patenting temperature; the difference, in short, between cooling in air and cooling in lead, in damp sand or in an air blast.

From the mass of evidence now available to illustrate the effect of varying the rate of cooling in the patenting process it is difficult to select examples.

Perhaps the best illustration is obtained by comparing the physical properties of wires made to the same specification (*a*) by cooling in air, and (*b*) by cooling in

lead, the two methods generally used. This may be done either by using the same steel and drawing the air-cooled wire a little more than the lead-cooled wire, or by using a steel of lower carbon content when lead cooling. The latter method is the one most commonly adopted: first, because it enables one to make the fullest possible use of the carbon in the steel; and second, because the reduction by drawing can be standardised. A steel containing 0·35 per cent. carbon when lead cooled at 350° C. will give a wire of about the same tensile strength as a steel containing 0·45 per cent. carbon air cooled when the reduction by drawing is similar. The microstructures of the steel wires in the patented condition are shown in Figs. 41 to 44. At low powers they appear almost identical in spite of the carbon difference. At high powers the difference is evident in the pearlite or sorbite constituents. The physical properties of such wires at various stages in reduction are given in Table 2.

TABLE 2

Material	*Reduction by Drawing* = %	*Max. Stress Tons per square inch*	*Bends 7·5 mm. radius*	*Torsions 100 Diameters*	*Limit. Fatigue Stress Tons p. sq. in.*
0·36% C. L.C.P.	Patented	54·5	29	..	±19·3
0·46% C. A.C.P.	,,	50·4	28	..	±18·9
0·36% C. L.C.P.	25	66·5	32	90	±18·3
0·46% C. A.C.P.	,,	62·8	22	60	±20·0
0·36% C. L.C.P.	50	72·5	34	79	±21·9
0·46% C. A.C.P.	,,	67·8	25	44	±21·5
0·36% C. L.C.P.	75	81·0	31	50	±24·1
0·46% C. A.C.P.	,,	78·5	25	40	±23·9
0·36% C. L.C.P.	80	86·9	29	..	±25·2
0·46% C. A.C.P.	,,	82·3	24	..	±23·8
0·36% C. L.C.P.	85	93·7	26	..	±24·6
0·46% C. A.C.P.	,,	86·1	22	..	±23·6
0·36% C. L.C.P.	90	103·8	23	36	±23·9
0·46% C. A.C.P.	,,	90·0	21	30	±23·6

More direct comparisons between air and lead cooling in the same steels are given in Tables 3 and 4.

TABLE 3

The Effect of Drawing on the Mechanical Properties at Various Stages in Reduction of 0·30 per cent. Carbon Steel Wire Patented in No. 2 S.W.G., 0·276 in. Diameter

No.	Diameter Inches	Reduction by Drawing per cent.	Maximum Stress Tons per sq. in.	Torsions 100 D.	Reduction of Area at Fracture per cent.	Bends
Cooled in Lead at 350° C.				Mean of Three Tests		7-mm. radius
1	0·276	*nil*	42	..	..	..
2	0·151	70·0	70	46	53·0	10
3	0·128	78·5	75	43	50·0	12
4	0·109	84·8	80	39	56·5	16
5	0·092	89·0	85	41	50·0	19
						5-mm. radius
6	0·075	92·3	95	38 40 33	46·0	10
7	0·063	94·8	104	41 39 40	44·0	13
8	0·054	96·2	113	37 34 36	..	15
9	0·042	97·7	133	27 27 27 / 31 30	..	34
Same Material Air Cooled.						7-mm. radius
10	0·276	*nil*	37	..	..	..
11	0·151	70·0	62	37	42	7
12	0·128	78·5	66	35	35	8
13	0·106	85·0	70	37	37	11
14	0·092	89·0	77	39	37	13
						5-mm. radius
15	0·072	92·5	91	36	37	8
16	0·062	95·0	94	34	30	9
17	0·051	96·5	105	32	..	11
18	0·040	98·0	114	20	..	23

TABLE 4

Average Results of Air-Cooled and Lead-Cooled Wire after each Pass in Drawing

	C	*Si*	*Mn*	*S*	*P*
Analysis of Steel	0·44	0·06	0·82	0·036	0·031

Air Cooled						*Lead Cooled*					
Reduction per cent. by Drawing	*Diameter Inches*	*Maximum Stress Tons per sq. in.*	*Reduction of Area per cent.*	*Torsions on 100 Diameters*	*Bends*	*Reduction per cent. by Drawing*	*Diameter Inches*	*Maximum Stress Tons per sq. in.*	*Reduction of Area per cent.*	*Torsions on 100 Diameters*	*Bends*
nil	0·160	49·0	47·0	..	..	*nil*	0·160	52	48	34·0	..
24	0·139	58·0	48·0	35	6	23	0·140	58	50	25·0	6
43	0·121	64·0	46·0	31	7	43	0·121	65	48	28·0	8
60	0·101	70·0	51·0	37	7	54	0·108	67	53	32·0	10
70	0·087	77·0	51·5	38	11	65	0·0955	73	55	33·0	12
79	0·073	82·0	45·0	39	16	75	0·079	80	56	38·0	15
85	0·061	88·0	49·0	38	19	85	0·061	89	55	40·0	24
90	0·049	100·0	45·0	38	18	91·5	0·047	105	55	38·0	28
94	0·040	109·0	38·0	35	18	94·5	0·038	123	40	36·0	34
96·5	0·0295	135·5	32·0	31	17	96·5	0·030	141	41	33·5	34

The effect of cooling in lead is even more striking in the case of higher carbon steels. In the manufacture of high tensile wire for springs and pianos lead cooling, or its equivalent, is almost essential, although an increase in the manganese content of the steel to about 1 per cent. greatly increases the efficiency of air cooling.

Some figures taken from a recent paper by Gill and Goodacre [15] are plotted in Fig. 57 in such a way as to show the comparative effect of air and lead cooling on the limiting fatigue stress in wire of the following composition:

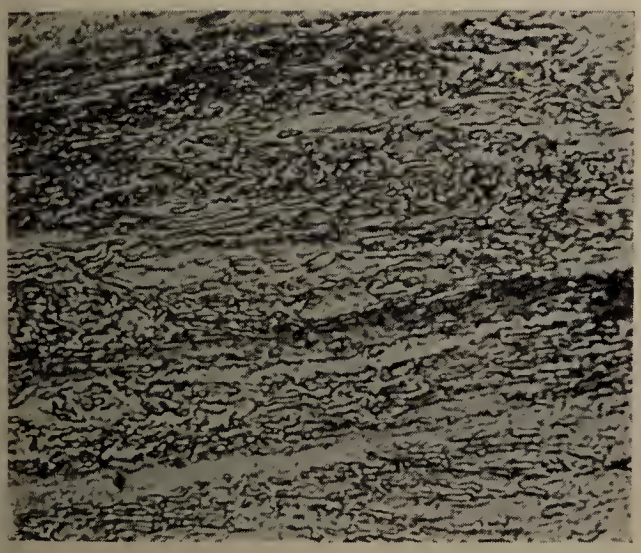
C	*Si*	*Mn*	*S*	*P*
0·79	0·25	0·49	0·011	0·024

in which all traces of decarburisation were removed by grinding in the patented condition.

The structural difference between wires cooled in air and in lead is not very obvious, particularly at low magnifications. In medium carbon steels a slight difference in the amount of free ferrite is all that can be detected, this point of distinction being more evident in thick than in thin wires. In higher carbon steels

Plate XIII.

45



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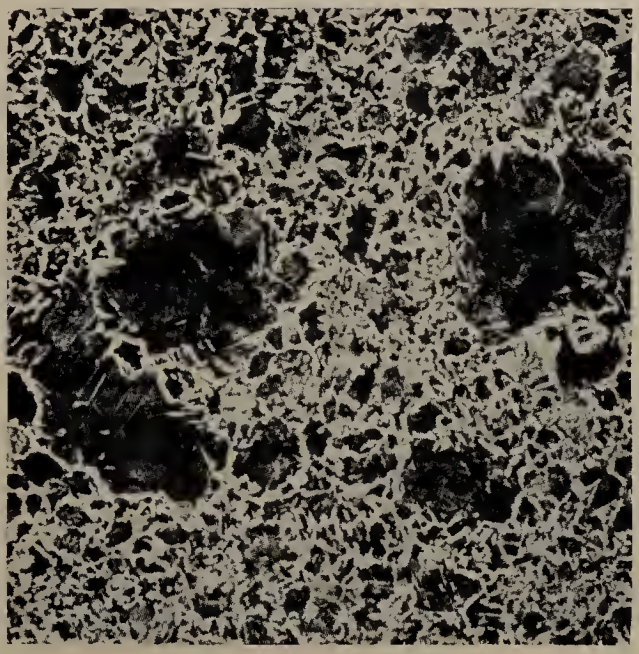

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Fig. 45. LONGITUDINAL SECTION 0.80 PER CENT. CARBON STEEL WIRE. ANNEALED AND DRAWN 2 PASSES. NOTE IRREGULAR FLOW OF LAMINATED STRUCTURE. Magnified 550 Diameters

Fig. 46. LONGITUDINAL SECTION 0.70 PER CENT WIRE SHOWING SORBITIC STRUCTURE IN DRAWN CONDITION. Magnified 2,000 Diameters. Etched 10 minutes in Glacial Acetic Acid.

Fig. 47. 0.43 PER CENT. CARBON STEEL WITH MANGANESE CONTENT OF 0.39 PER CENT. SHOWING IRREGULAR GRAIN STRUCTURE DUE TO TOO LOW PATENTING TEMPERATURE. CARPENTER & ROBERTSON. Magnified 100 Diameters

there is no free ferrite in either, and high magnification is necessary to distinguish a lead-cooled from an air-cooled wire; even then the difference at any one point is not very evident, and only a diligent survey of the whole section will serve to show the difference between the two structures and to explain the superiority of the lead-cooled wires. The most striking feature of the structure of such lead-cooled wires is the homogeneity in the condition of the sorbite. In an air-cooled wire, on the other hand, while there are many portions similar in appearance to the general structure of the lead-cooled wires, there are other portions where evidence of slower cooling conditions have produced the laminated variety of pearlite. Of course, the appearance of laminated grains here and there does not necessarily mean that these have been cooled more slowly than their neighbours, because the appearance of each crystal largely depends on its orientation—a point recently emphasised by Belaiew; but it does indicate slower cooling in general, and, to some extent at least, a less uniform chilling. It is the author's belief that the more perfect homogeneity of the sorbite in the lead-cooled wires explains their superiority in physical properties, particularly emphasised in the reverse bend tests given below, which have been averaged from many thousands of test records on wires of sizes ranging from about 12 S.W.G., or 0·104 inch diameter, up to ½ inch.

Treatment	*Reverse Bend round Radius of 3 Diameters*
Air cooled and drawn . . .	5
Lead cooled and drawn . . .	9

The importance of uniform flow in wire-drawing cannot be too strongly emphasised, and nothing shows this so clearly as the reverse bend test. The various structures referred to above are illustrated in Figs. 36 to 46.

Comparing the flow of sorbite and pearlite, in his paper on "Heat-Treatment and Cold Work," [16] the author said:

"The structure of sorbite is for the most part granular, and although high magnification shows some signs of lamination, especially when cooling has not been sufficiently rapid, these are of a much finer nature than the laminations of normal pearlite. These constituents are aggregates consisting of ferrite and carbide, which have separated from solution.

"When laminated pearlite is subjected to cold work, the flow or slip must take place in the direction of the laminations, and in many of the grains the direction of the laminations is opposed to the general direction of flow; hence great irregularity of movement must take place.

"In sorbite, however, the hard constituent exists as small particles intimately mixed with the soft iron, the whole structure being a fine network. The carbide exercises a restraining influence on the flow of the ductile constituent, while at the same time the flow of the soft iron is not inhibited. It is the possibility of moulding the whole internal structure to the line of flow that makes the movement in each grain more uniform and prevents the development of internal stresses and fissures."

SUMMARY

The following conclusions regarding the heat-treatment of high tensile wire were reached fifteen years ago, and are reproduced here by way of recapitulation, with only one minor modification:

(1) The capacity to withstand cold work is largely determined by the microstructure and cannot be indicated entirely by the physical properties of the material; indeed, material in a suitable condition for wire-drawing has, at first sight, poor physical properties.

(2) In a properly drawn steel wire the crystalline grains are not destroyed, but are elongated into fibres. Cold flow takes place within the grains and only incidentally by slip at the grain boundaries. There must, however, be movement at the boundaries accompanying the internal movement of the grain, and this intergranular movement will be greater or less according to the irregularity or uniformity of the internal flow. When this irregularity is great, rupture will occur either at the boundary or through the grain and the material will be weakened.

(3) When the grain is fully elongated into a fibre it cannot be subjected to further cold work in the same direction without rupture, and when this occurs to any serious extent the material is overdrawn. This does not appear to apply to very ductile pure metals and alloys which can be drawn long after all fibre identity is lost.

(4) When an attempt is made to reduce the material too much at one pass the grains are broken, as in a tensile test, before the internal structure can adjust itself to the movement.

(5) When the grains are very small, as in steels tempered after previous cold work or by drastic quenching, they have not the same capacity for elongation. Hence a fine-grained structure is not suitable for cold working.

(6) A coarse-grained structure has the greatest capacity to elongate into unbroken fibres, but, since such a structure is usually associated with overheating and "ingotism," it is not desirable in the finished material.

(7) The structure most suited to flow uniformly and to withstand the greatest reduction by cold work, such as in wire-drawing, is one in which the grains are large enough to elongate into fibres, and consists throughout of granular sorbite. The statement that the capacity to withstand reduction by cold work decreases with increase of carbon content is not at all universally true. In fine wires, where the flow is more or less uniform throughout the section, it is doubtless true. It is true also when the material is in the annealed condition, but in thick rods or bars the more uniform flow of the sorbitic condition permits of greater reduction by cold work.

(8) A structure consisting entirely of laminated pearlite, such as obtains in annealed eutectoid steels, is quite unsuitable for wire-drawing.

(9) The high temperature employed for the heat-treatment operations in the manufacture of carbon steel wire is quite justified, and it would seem that 1000° C. is a suitable average temperature.

(10) The structural effects of cold work are not removed by annealing or tempering below the critical range, and such a process cannot replace "patenting."

The above summary admittedly deals with the matter from the heat-treatment and metallographic aspect only and does not profess to explain the entire mechanism of plastic flow, which is entirely another matter.

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CHAPTER V

EFFECT OF COLD WORK ON THE PHYSICAL PROPERTIES OF METALS

It is unnecessary at this stage to enlarge in a general way on the now well-known fact that the plastic deformation of metals by cold working has a profound influence on the physical properties.

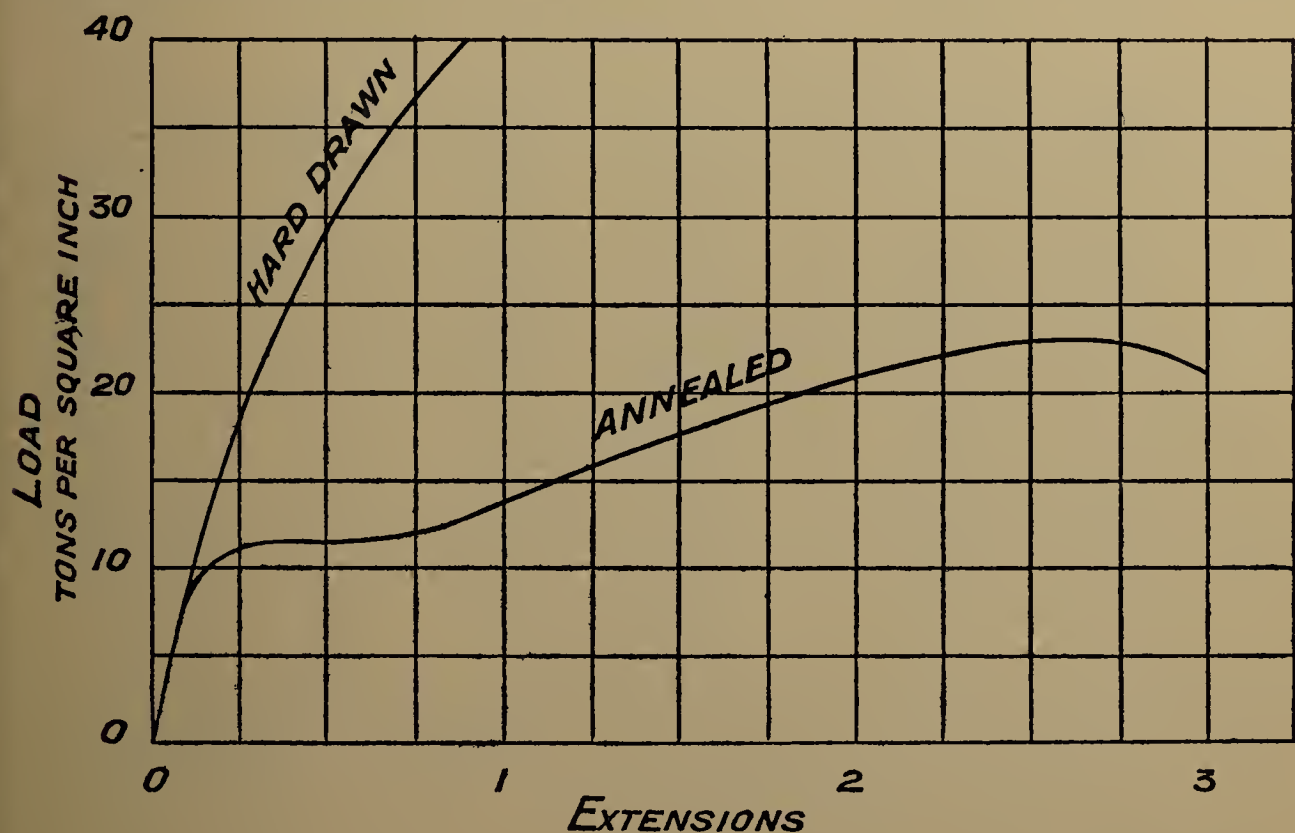

Fig. 48

Nothing, perhaps, illustrates so well how completely altered a metal is after cold work as a comparison of the stress-strain diagrams of a mild steel in the annealed and in the hard-drawn condition (Fig. 48). The differences represented so graphically in these diagrams suggest that the cold-worked steel is a new material, and so in a purely physical sense it is, although chemically it appears unaltered.

There are, however, certain chemical effects which result from the cold working of iron and steel which are of interest.

Whiteley and Hallimond [1] have studied the solution of iron in nitric acid from this point of view, and have shown that this process affords a delicate test for the

detection of cold-strained material. The chief gaseous products formed in this solution are ammonia, nitrogen, and nitric oxide (NO).

The amounts of these gases vary appreciably with the condition of the iron or steel and with the conditions under which the metal is dissolved. Using certain standard conditions specified, it is found that from annealed material much more nitric oxide and much less ammonia and nitrogen are obtained when the acid strength exceeds about 24 grms. per 100 c.c. than is the case with lower acidities. At that concentration there is a very abrupt alteration in the nature of the gases evolved, as is indicated in the table below:

Acid Strength Grammes per 100 c.c.	*Volume of the Gases formed, c.c.*		
	NH_3	N_2	NO
21·5	18·2	8·0	39·0
26·3	3·0	5·8	83·0

This abrupt change, however, no longer holds for cold-worked material, such as drillings or cold-drawn wire. The proportion of the iron used, which is responsible for the formation of nitrogen and ammonia, is, with acid strengths up to about 15 grms. of nitric acid per 100 c.c., about two-thirds of the total iron dissolved, 0·3 grms. in all. The remainder of the iron in its solution forms other gases, chiefly nitric oxide, together with small amounts of nitrous oxide (N_2O) and nitrogen peroxide (NO_2). It is clear that the method will detect the cold-worked material with ease.

The increased amount of iron which in its solution forms ammonia and nitrogen as the amount of cold work is raised is shown in Table 5, which refers to an ingot iron.

TABLE 5

Treatment	*Diameter of Wire cms.*	*Percentage Reduction of Area*	*Weight of Iron which forms N_2 and NH_3 in grammes*
Hot rolled . . .	0·52	0	0·056
1st drawing . . .	0·40	41·0	0·107
2nd ,, . . .	0·31	64·5	0·123
3rd ,, . . .	0·265	74·0	0·133
4th ,, . . .	0·194	86·0	0·137
5th ,, . . .	0·163	90·0	0·142

The continuous increase in the relative amounts of nitrogen and ammonia formed as the wire is more and more deformed will be clear.

Annealing the drawn wire results in the reversion of the gases to those of the

hot-rolled rod, and when the temperature of annealing has reached 520° C. the composition of the gases produced is the same as that for the initially annealed metal.

The method of investigation will be seen to be comparatively simple and to show the effects of even the smallest amount of cold work. It is also applicable to the determination of the temperature at which cold-worked material has been blued, a point almost impossible to determine microscopically.

Turning now to the physical properties, what we have to consider in some detail is how exactly the individual properties are modified and what bearing other factors, such as composition of the metal and preliminary treatment, have on the final result. Finally, we must consider the altered properties in relation to one another and their relative importance according to the use to which the cold-worked product is to be put.

HARDNESS

The most noticeable effect of cold work on metals is the decrease in ductility and malleability. When a metal is hammered or rolled we say it becomes "hard," and if a wire is left as drawn and not annealed it is called a "hard-drawn wire."

When we come to analyse this "hardness," however, we find it consists merely of an increased resistance to further cold flow. There is undoubtedly a stiffening of the whole mass—a change from the soft plastic condition of the annealed metal to a tough and more springy one.

Regarded in the mass, metals are undoubtedly hardened by cold work, but the results of hardness tests depend on the dimensions of the area tested. Thus, an area which gives a certain hardness value under the ordinary Brinell test may be found to vary greatly at different points when tested on a much finer scale with the diamond pyramid tester by the micro-sclerometer as shown by Boynton [2] or by the scratch tests as shown by Tammann. Tests carried out at Sheffield University by Goodacre, Merrils, and others with the Vickers diamond pyramid tester show that the hardness of wire varies considerably throughout its cross-section, and that this varying hardness is not entirely the result of cold work but is also evident in the original patented rod. Fig 49 shows typical hardness curves obtained in this way: (1) on the wire as patented, (2) on the wire as drawn. This hardness variation can hardly be considered surprising in view of the internal strains set up by heat treatment, and it is to be expected that cold working would intensify these differences.

What bearing, if any, these results have on the problems of cold working remains to be seen. Though the areas tested in this way are very fine in comparison with the areas covered by the Brinell test they are nevertheless extremely coarse compared with those covered by the individual micro-constituents of sorbite, and it is in the behaviour of these micro-constituents under cold flow and finally in the distortion of the atomic space lattice that the mechanism of cold flow must be sought. Here we are concerned only with the general hardening of the metal in the mass by cold work as determined by such tests as the Brinell, Scleroscope, and others bearing on the machining and wearing properties of wire.

TABLE 6

Pyramid Diamond Hardness of Drawn Wire co-related with Tensile Strength

Diameter in inches	*Maximum Stress in Tons per sq. in.*	*P.D.H. Number*	*P.D.H. / Maximum Stress*	*Reduction of Area by Drawing*
				Per cent.
0·217	44·2	214	0·207	Lead patented
0·182	55·2	246	0·224	29
0·160	55·5	255	0·218	45
0·135	65·0	266	0·244	61
0·115	68·8	280	0·246	72
0·097	73·5	312	0·236	80
0·080	80·0	328	0·244	86
		0·55 *per cent. Carbon Steel Wire*		
0·212	59·9	270	0·222	Lead patented
0·183	69·4	294	0·235	26
0·160	74·8	305	0·245	43
0·135	80·9	318	0·254	59
0·116	85·7	350	0·245	70
0·098	92·6	365	0·254	78·5
0·080	104·5	405	0·258	86
		0·83 *per cent. Carbon Steel Wire*		
0·224	76·6	384	0·20	Lead patented
0·190	88·5	390	0·196	28
0·166	96·7	381	0·254	45
0·144	101·6	426	0·238	58·5
0·125	106·6	456	0·234	69
0·108	116·0	475	0·244	77
0·097	121·0	488	0·248	81
0·080	137·5	543	0·253	87
0·134	86·7	427	0·203	Lead patented
0·120	96·0	452	0·212	20
0·103	103·0	464	0·222	41
0·083	117·0	495	0·236	62
0·071	123·0	551	0·223	72
0·061	130·0	594	0·219	79
0·052	145·0	598	0·243	85
0·040	169·0	671	0·252	91

Brinell tests show, on the whole, a fairly steady increase of hardness in the mass, roughly proportional to the amount of cold work and to the ultimate strength. This is illustrated in Table 6.

Although machineability and wear resistance of wire are not entirely dependent on hardness, the relationship is sufficiently close to make some consideration of these properties appropriate here.

It is well known that the extreme softness of iron and mild steel in the annealed

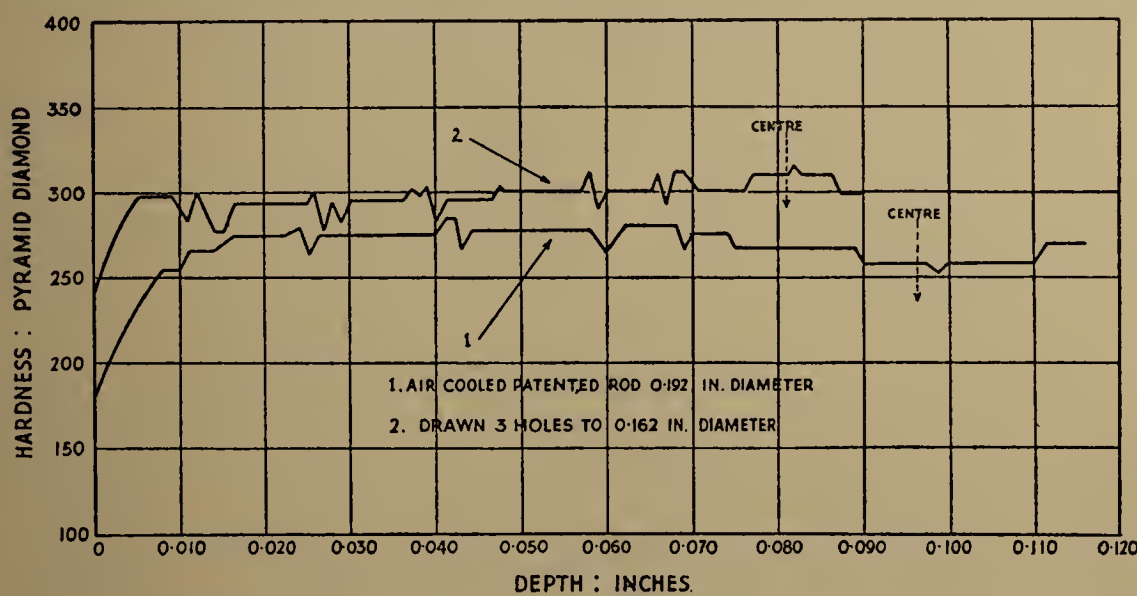

Fig. 49

condition is not conducive to ease in machining. Thus mild steels are more easily machined when hardened by cold work.

Carbon content and patenting affect the machineability profoundly, and it is generally considered inadvisable to produce patented steel wire beyond 65 tons per square inch tenacity when machining is essential. In this connection the author's experience is that when machineability is important the desired tenacity should be obtained by cold work rather than by increased carbon content and heat-treatment. For example, in the production of aircraft wires which have to be screwed, it is better from this point of view to use a steel with a carbon content as near the minimum specified as possible and to cool in air instead of in lead after patenting. Lead cooling undoubtedly increases the difficulties of machining, presumably because it makes the wire tougher; but the effect of lead cooling on the machineability may be counteracted to some extent by decreasing the carbon content. Unfortunately specifications often tend to be unnecessarily restrictive and prevent the progressive manufacturer from putting into practice some modification which research work has shown to be desirable, because this modification involves a departure from a specification on some point such as minimum carbon content.

The matter of resistance to abrasion is also of considerable importance in rope wire, and some discussion of this point is made in Chapter VIII.

TENACITY

Probably the most important effect of cold working, and of wire-drawing in particular, is the increase in tensile strength. In no other way can the tenacity of metals be increased to such an extent as by wire-drawing. It is not a very difficult matter to produce a wire with a tensile strength of 200 tons per square inch, and even higher figures than this have been reached. This is, of course, due to the carbon content and heat-treatment, the maximum stress of the steel before drawing in

TABLE 7

Material	*Tensile Strength Tons per square inch*		*Source*
	Annealed or Heat-treated	*Hard Drawn*	
Gold	7	15·6	Beilby [3]
Silver	11	25·7	Beilby
Copper	14	41·6	Bolton [4]
Phosphor bronze	22	65·0	Author
Nickel	30	70·0	Bureau of Standards
Monel metal	35	65·0	Author
K. Monel	..	80·0	,,
Ingot iron	20	60·0	,,
Mild steel (free cutting)	36	112·0	Longmuir [5]
0·50 Carbon steel	53	180·0	Author
0·85 Carbon steel	90	250·0	,,

such a case being about 90 tons per square inch. The strength of hard-drawn copper wire is generally about double that of the annealed wire. Thus ordinary commercial copper with an initial strength of 14 tons per square inch can be drawn into wire with a strength of nearly 30 tons per square inch. Roughly speaking, the tenacity of a hard-drawn wire of any metal is proportional to the original strength of the metal and to the amount of reduction it has received. All alloys, however, cannot be hard drawn to the same extent, and some, which do not lend themselves to drawing, cannot be increased very greatly in strength by cold working. Nickel is an example of a malleable metal which is apt to give trouble in drawing, and some of its alloys also present difficulties. For example, Monel metal, although it has in the normal condition a strength slightly greater than that of mild steel, cannot be hard drawn to the same extent. Recently a new Monel metal alloy

called K. Monel has been put on the market in the form of wire with a tensile strength of about 80 tons per square inch. Phosphor bronze is an alloy that gives exceptionally good results in drawing. Cold-drawn phosphor bronze wire with a strength of 60 tons per square inch can be produced—an increase of more than 200 per cent. from the annealed condition.

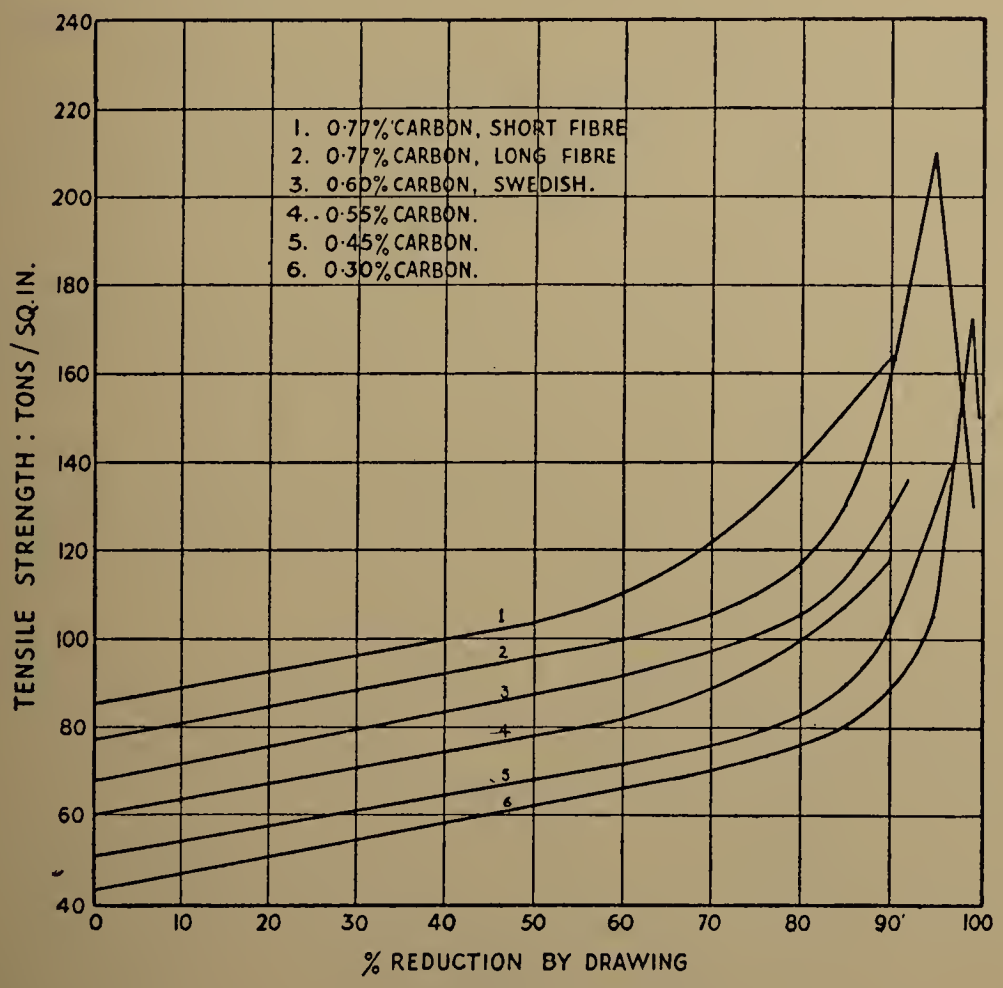

Fig. 50

Table 7 sets out the approximate maximum stresses of various metals and alloys in the hard-drawn condition as compared with that in the annealed state, the source of figures for the hard-drawn condition being indicated in the last column.

These figures represent approximately the extreme increase in tenacity which can be obtained in each metal, and wire drawn to this extent is, from the commercial point of view, overdrawn and therefore brittle. In most metals there appears to be three important stages in drawing:

(1) The point of maximum efficiency, where the greatest tenacity consistent with the required toughness is secured. This point naturally varies with circumstances—such as heat-treatment, system of drafting, nature of metal, and purpose for which it is intended, etc.

(2) The point of maximum tenacity.

(3) The point of breakdown, beyond which the wire cannot be drawn.

The point of maximum tenacity does not necessarily coincide with the point of breakdown, beyond which the wire cannot be drawn. In most cases there is an actual decrease in tensile strength from the maximum before the latter point is reached. Thus G. T. and H. N. Beilby found it possible to overdraw a wire so that its tenacity, having passed a certain maximum, began definitely to fall. The highest tenacity in gold was developed by drawing it to $3\frac{1}{2}$ times its original length, but by drawing it to as much as 13 times the tenacity was only slightly reduced. Brunton [6] also found the same thing in steel wire which had received as many as 17 passes, although in steel the point of maximum tenacity is much nearer the point of rupture than in gold. The complete history of drawing on the tenacity of a steel of the piano wire variety from the patented condition to the point of breakdown is clearly shown in curve 2, Fig. 50. This curve is interesting from many aspects, but the point of importance here is that the maximum tensile strength of 210 tons per square inch reached in this case is practically identical with that recorded for similar wires by Atkins and Watertown Arsenal.

Higher values have been reached in finer wire. For example, in wire 0·008 inch diameter the author obtained a tensile strength of 250 tons per square inch.

The maximum cold work which a metal will stand, and the consequent increase in tenacity for that particular metal, depends on a great many different factors. To name a few it depends on:

The methods of cold working.
The dimensions of the material.
Its chemical composition.
Its microstructure, dependent on heat-treatment.
The stages of reduction.

The capacity of metals, and steel in particular, for withstanding cold work has, indeed, been generally underestimated, and even when the possibility of obtaining an enormous increase in tensile strength by wire-drawing has been recognised there is a general feeling that this has only been obtained at such expense of other properties as to make very hard-drawn wire unsafe for use. To what extent this is true depends on the above-mentioned factors, and in this chapter these must be taken into consideration.

Of all cold-working methods wire-drawing is the most effective in modifying the physical properties. In practice there is a mechanical limit to the amount of cold work which can be applied to metals; this is particularly so in regard to cold rolling, and even in wire-drawing it is often the impossibility of getting the die to hold out rather than the failure of the wire that puts an end to drawing.

On the size of the wire also depends the tenacity obtainable by cold work. The influence of this factor may be illustrated by the following three examples of medium carbon steel which the author has had drawn at different periods:

TABLE 8

Influence of Diameter on Drawing

Sample	*Diameter in inches*	*Maximum Stress Tons per square inch*	*Reduction per cent. by Cold Work*
	Analysis.—C = 0·49%; Si = 0·13%; Mn = 0·65%; S = 0·037%; P = 0·039%		
1. Before drawing .	1·250	50 (approx.)	
After drawing . .	0·575	92·8	79·0
	Analysis.—C = 0·55%; Si = 0·12%; Mn = 0·54%; S = 0·042%; P = 0·037%		
2. Before drawing .	0·432	53·0	
After drawing . .	0·138	134·0	89·0
	Analysis.—C = 0·44%; Si = 0·06%; Mn = 0·82%; S = 0·036%; P = 0·031%		
3. Before drawing .	0·160	53·0	
After drawing . .	0·028	180·0	96·5

In each case drawing had to be discontinued before the wire broke, and it is probable that slightly higher tenacities might have been reached by varying the drawing conditions. The figures, however, represent approximately the effect of diameter on the maximum tenacity attainable by cold drawing. Expressed in round numbers, and in terms of the standard wire gauge, these are:

Gauge . . .	7/0 or ½ inch	12	35
Tenacity . .	100	150	250 tons per sq. in.

Chemical composition is naturally the most important factor in determining the effect of cold work on the tenacity, and its effect has already been indicated in Table 7. The effect of composition is, however, modified considerably by the fourth factor, viz.:

Microstructure.—Since this factor has been considered already in Chapter IV. it is only necessary here to illustrate its influence by two examples. The effect of structure is striking only in steels beyond the range of mild steels. Of the two examples which are chosen to illustrate the importance of structure on the cold-working properties, and therefore on the tenacity and other physical properties, one is a steel containing 0·50, the other 0·85 per cent. carbon, and the data regarding these samples are given in Table 9.

TABLE 9

Analysis per cent.	*Treatment and Structure*	*Original Diameter Inches*	*Final Diameter Inches*	*Maximum Stress Tons per square in.*	*Elongation on 2 in. per cent.*	*Reduction of Area per cent.*	*Reduction by Cold Working per cent.*
Carbon = 0·50 Silicon = 0·13 Manganese = 0·65 Sulphur = 0·037 Phosphorus = 0·039	Annealed 60 per cent. pearlite, 40 per cent. ferrite	1·25	0·833	66	7·5	1	57
	Limit of drawing; bar broke at this point with "cuppy" fracture						
	Patented 90 per cent. sorbite, 10 per cent. ferrite	1·25	0·575	92·8	7	12	79
	Bar not fractured; die would not stand further reduction						
Carbon = 0·85 Silicon = 0·12 Manganese = 0·30 Sulphur = 0·022 Phosphorus = 0·020	Annealed laminated pearlite	0·16	0·127	60	..	*nil*	37
	Limit of drawing; wire broke at this point						
	Patented sorbite	0·16	0·053	148	..	28	89
	Wire not fractured; could have been drawn further						

Stages of Reduction.—The last factor of those we have named above is a particularly interesting one, which has already been discussed to some extent. It has a direct and an indirect influence on the tenacity. The direct effect of drawing or rolling in easy stages is to reduce the effect on the physical properties; thus of two similar wires drawn to the same size from the same original diameter, one in 5 passes and the other in 10 passes, the latter would have a lower tenacity than the former. On the other hand, the more gradually a wire is reduced the more cold work it will stand, so that indirectly light draughting ultimately increases the tenacity of a wire. This is clearly illustrated by Longmuir (see Fig. 51), which shows the effect of drawing by reductions of only 0·001 inch diameter at each draught on the tenacity of three different steels.

(1) A mild steel of the "free cutting" type is drawn till it attains a maximum stress of 112 tons per square inch, a result which is scarcely possible with ordinary draughting.

(2) Two carbon steels in the annealed condition are drawn to a much greater extent than is possible with ordinary reductions, except when the steels are patented and have a sorbitic structure. In these two wires it has been possible to draw the laminated pearlite only because the reduction has been made in extremely light draughts.

It is interesting to compare the bottom curve in Fig. 51, which shows the total reduction obtained in Longmuir's high carbon wire, with the result obtained by

the author on a similar steel drawn in the ordinary way (see example 3 in Table 9). In the latter case it has been possible to draw the annealed wire only 2 ordinary passes, whereas Longmuir has been able to draw his wire very much smaller, because his reduction at each pass was only 0·001 inch diameter.

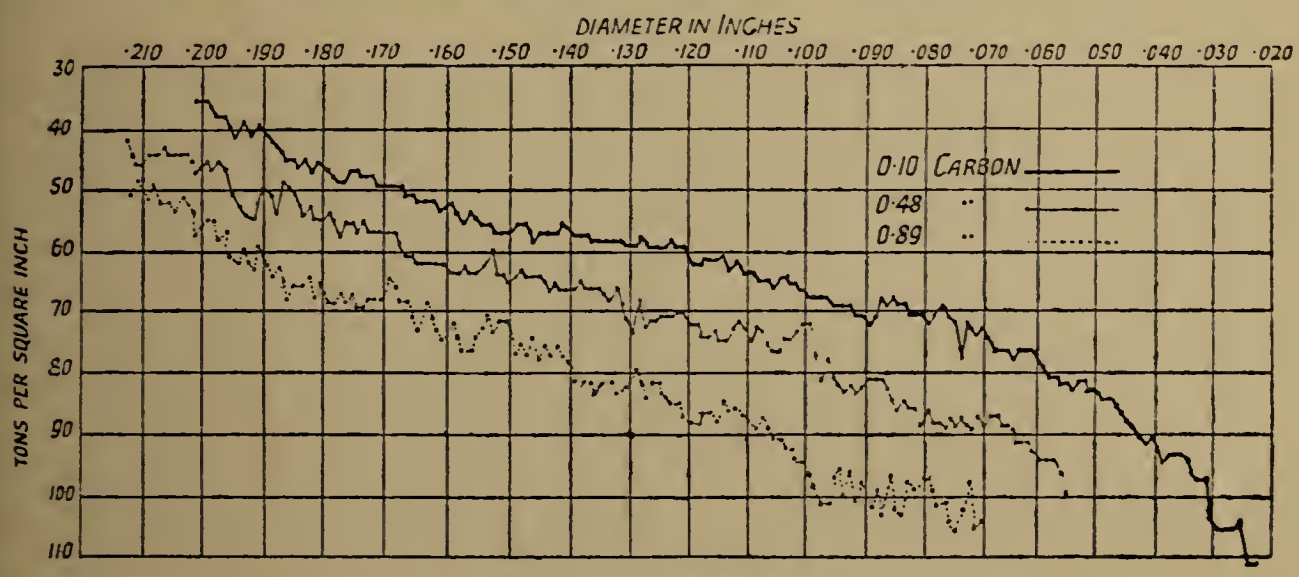

FIG. 51. (LONGMUIR.)

This effect of the nature of the draughting is well shown by the following figures due to Atkins. The samples were dead mild steels with 0·10 per cent. carbon and about 0·5 per cent. manganese. It will be seen that the tensile strength of the wire drawn down from 5-gauge rod to 14-gauge by heavy holing in 4 passes is as high as that of the 18-gauge reduced in 8 light draughts.

Gauge	*Maximum Stress— Heavy Holing*	*Tons per square inch— Light Holing*
Hot rolled 5-gauge rod	27	22
8	..	33
8½	42	..
9¾	..	37
10½	49	..
10¾	..	43
12¼	53	..
13½	..	47
14	65	..
15	..	50
16¼	..	53
17¾	..	62
18	..	65
20	..	68

A further comparison between heavy and light holing in armco iron will be found in Table 13, and in patented steel wire in Table 10.

TABLE 10

Effect of overdrawing Wire by Reducing too much at each Pass on 0·65 per cent. Carbon Steel

	Number of Passes	*Reduction in Area per cent.*	*Diameter in inches*	*Maximum Stress Tons per square inch*	*Torsions on 100 Diameters*	*Bends 5 mm. Radius*
Heavy holing .	1	44	0·142	82·7	5	2½
Light ,, .	3	44	0·143	73·8	15	5
Heavy ,, .	2	42	0·112	90·4	11	4½
Light ,, .	6	48	0·103	88·0	15	7
Heavy ,, .	3	47	0·080	106·0	8	2½
Light ,, .	8	38	0·081	95·0	38	11

From these remarks it will be seen that the effect of cold work on the tenacity of metals is a complex matter, depending on so many factors that no hard and fast rules can be laid down to guide one in drawing or rolling to a certain strength.

Although the wire manufacturer has to be guided by his own experience in meeting specifications, there are one or two formulæ which can be applied as rough guides. It is not a difficult matter, for instance, to prepare a chart giving the approximate tensile strengths of rods and wires in the patented condition. This can be obtained by co-relating actual tests with steel composition, including carbon, silicon, manganese, and phosphorus contents, as done by Campbell, and later modified by McWilliam for normalised bars. Given this initial value the increment due to drawing is surprisingly constant for all sizes and steels within the ordinary limits of the trade. This will be evident from the slopes of the curves in Fig. 50. For the straight portion of these the simple formula $y = c + x \tan \theta$ can be used where

y = the tenacity of the finished wire;
c = ,, ,, patented wire;
and x = the percentage reduction in area.

Thus for curve (6) the value of $y = 42{\cdot}5 + {\cdot}393\,x$ and the average value of $\tan \theta$ for the whole of the curves is approximately 0·375. Since in practice, however, most wire is drawn beyond the straight portion of the curves an average increment of 0·45 tons for each per cent. reduction in area is probably nearer the truth. K. B. Lewis states that an increment of 1000 lbs. per square inch for each per cent. reduction is the figure used in the United States.

As a rough guide an increase of 5 tons per square inch for each gauge drawn is useful, but the above figures hold only within such limits as the curves in Fig. 50 suggest.

DUCTILITY

Wire-drawing increases the tenacity of metals and reduces the ductility. It does not follow, however, that the greater the strength of a wire the lower is its ductility. A wire with a tensile strength of 100 tons per square inch may be more ductile than another wire with a tensile strength of only 50 tons per square inch.

The whole question of the relative importance of tenacity and ductility is a difficult one, involving the discovery of the point of maximum efficiency or optimum point in drawing in wire for different purposes. Ductility is a term which is difficult to define. It has been defined as the property which enables a substance to be drawn out as in a wire; yet this scarcely covers every form of ductility. Speaking in a broad way, one may call all tests, such as bending, twisting, stretching, etc., ductility tests; yet a metal which stands bending may not stand twisting, and *vice versa.*

Everything depends on how the load is applied and the direction of the stresses. Ductility in metals then, in its widest sense, may be considered as the capacity for flow, but toughness rather than ductility is the essential property of high-grade wire. This somewhat elusive property of toughness is nowhere so marked as in steel wire. Not even the finest heat-treated alloy steels possess it to the same degree.

To the scientific man the unique character of wire is most clearly illustrated by the shape of its stress-strain diagram, to the practical man by the "snarl" test. It is our chief purpose to discover the meaning of this toughness and how it can best be determined by co-relating ductility with tenacity and elastic properties.

ELONGATION

Elongation is generally considered by the engineer the criterion of ductility, but this is based on experience with mild structural steels. Cold working, of course, reduces the elongation considerably, but the low elongation obtained on hard-drawn wire is not entirely the effect of cold working. Some reduction in elongation is caused by the reduced diameter of the test-piece. Roughly speaking, the elongation on a wire of 0·100 inch diameter in the annealed condition is only one-half that on the same material on a standard steel test-piece. Further reduction is due to the fact that the elongation is more localised in hard-drawn wire, and the gauge length of the test-piece used in measuring the elongation becomes specially important. On the purpose to which a wire is to be put, therefore, will depend the manner in which its elongation is measured and judged.

TABLE 11

	Condition	Maximum Stress in Tons per square inch	Elongation per cent.	
			On 10 inches	On 1 inch
a	As drawn	53·6	2·3	7
	Blued 1 hour at 350° C.	52·5	4·8	10
	Annealed	22·3	19·0	40
b	As drawn	79	1·6	7
	Blued 1 hour at 350° C.	79	5·2	12
	Annealed	31	20	30
c	As drawn	96	1·5	5
	Blued 1 hour at 350° C.	96	4·8	8
	Annealed at 600° C.	73·5	6·3	14
	Completely annealed	35·8	17·5	30

In Table 11 will be found some figures comparing the elongation on annealed drawn and blued wires:

(*a*) Of mild steel containing 0·16 per cent. C.
(*b*) Of medium steel containing 0·42 per cent. C.
(*c*) Of high carbon steel containing 0·80 per cent. C.

The size of the wires in each case is No. 12 Standard Wire Gauge, or 0·104 inch diameter.

Unless the gauge length is some geometrical proportion of the diameter, the results of elongation tests are meaningless.

The B.S.I. standard for gauge length is $4\sqrt{\text{area}}$, or approximately

$$\text{gauge length} = \text{diameter} \times 3{\cdot}54.$$

But this is quite impracticable when testing fine wires, since one requires a microscope to measure the result accurately. On the other hand, to specify a longer gauge length, such as 10 inches, for wire is misleading since nearly all the permanent stretch takes place within a very short length in the neighbourhood of the fracture. The amount of stretch *at a given load* over a certain length of wire is in many cases, such as in wire for railway signals, of great importance, but that is quite a different matter from taking the percentage elongation at fracture as a measure of the ductility of the wire.

No doubt in dealing with very fine wire the most practical and accurate way of measuring the elongation is to use an extensometer or strain gauge, and, since many of these are designed for a gauge length of 10 inches, this is used. Sometimes the elongation specified is the total elongation recorded on the gauge after fracture, but this of course includes elastic stretch.

Better results may be obtained when a strain gauge is used on a length of one or two inches only, and this is probably the only practical method of measuring

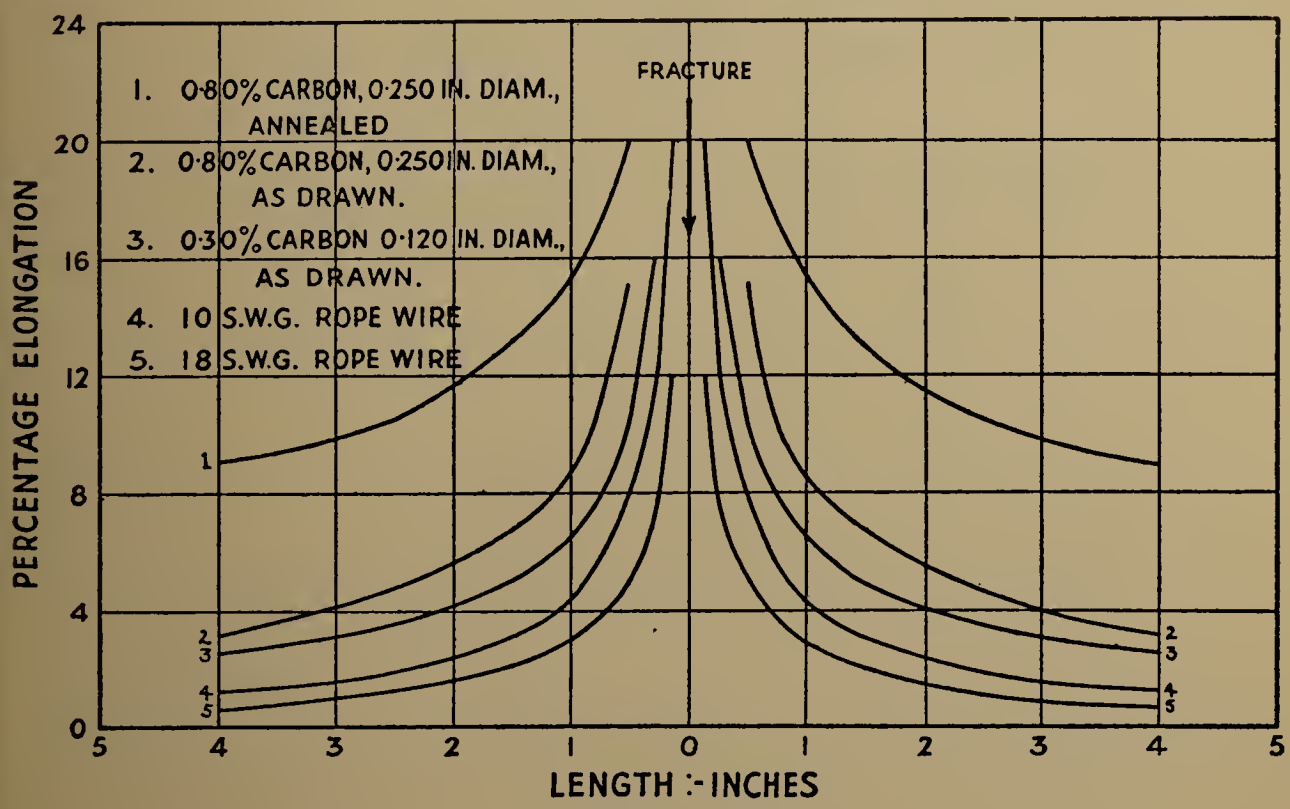

Fig. 52

permanent elongation on fine wire. The importance of the results, however, hardly warrants the trouble and time involved in making the test. With thicker wires the ordinary method of marking off the test-piece can be employed with reasonable accuracy, and in Fig. 52 some curves are plotted showing how the elongation on wires of different sizes varies with the gauge length. Beyond a certain gauge length there is little appreciable increment in elongation. This, it will be seen, is at the most equal to 20 wire diameters, and there is no object in using longer gauge lengths. In fact, most of the permanent stretch takes place within a length of 10 diameters, and this is a convenient gauge length to use in practice.

Goerens recognised the importance of gauge length in testing the elongation of wires and found that the first pass in drawing reduced the elongation considerably, the decrease becoming more gradual with subsequent passes. To reproduce all his results would occupy more space than the importance of the test warrants, but those on three of the steels he tested are given overleaf:

TABLE 12 (GOERENS)

Effect of Drawings on the Elongation

(Gauge Length approximately 10 times the diameter)

1. *Electric Steel of the following Composition :*

Carbon	*Manganese*	*Phosphorus*	*Sulphur*	*Silicon*
0·12	0·56	0·016	0·017	0·148

Hot rolled (untreated)	32·7 per cent.
Subjected to 1 drawing	15·6 ,,
,, to 2 drawings	13·7 ,,
,, to 3 ,, ...	10·2 ,,
,, to 4 ,, ...	6·7 ,,
,, to 5 ,, ...	6·0 ,,
,, to 6 ,, ...	6·0 ,,

2. *Open-Hearth Steel of the following Composition :*

Carbon	*Manganese*	*Phosphorus*	*Sulphur*	*Silicon*
0·55	0·47	0·068	0·036	0·262

Hot rolled	23·3 per cent.
1 pass	6·8 ,,
2 passes	5·9 ,,
3 ,, ...	6·5 ,,
4 ,, ...	6·0 ,,
5 ,, ...	6·3 ,,

3. *Open-Hearth Steel of the following Composition :*

Carbon	*Manganese*	*Phosphorus*	*Sulphur*	*Silicon*
0·78	0·38	0·016	0·019	0·113

Hot rolled	19·2 per cent.
1 pass	7·6 ,,
2 passes	6·9 ,,
3 ,, ...	5·9 ,,
4 ,, ...	6·2 ,,
5 ,, ...	6·0 ,,

Some figures for elongation at various stages in reduction in the drawing of armco iron wire are given in Table 13. It will be noticed that these figures, which were taken on a gauge length of $8\sqrt{\text{area}}$, or twice the B.S.I. standard, agree very closely with the results obtained by Goerens for mild steel, particularly in the case of the wires reduced in heavy draughts. The elongation falls suddenly after a single pass and then more gradually; indeed on the wire reduced in light draughts there is no decrease after the first pass.

TABLE 13

Table comparing Light Holing and Heavy Holing in Armco Iron

No. of Passes		*Diameter of Wire inches*		*Reduction per cent.*		*Maximum Stress Tons per sq. in.*		*Elongation per cent. on $8\sqrt{Area}$*		*Reduction of Area per cent. at Fracture*	
Light Holing	Heavy Holing	Light Holing	Heavy Holing	Light Holing	Heavy Holing	Light Holing	Heavy Holing	Light Holing	Heavy Holing	Light Holing	Heavy Holing
0	0	0·311	0·311	*Nil*	*Nil*	21·4	21·4	41·7	41·7	73·8	73·8
1	..	0·294	..	10·0	..	27·6	..	..	..	68·5	..
2	1	0·272	0·273	14·2	23·0	32·0	30·0	10·0	14·0	63·3	69·8
3	..	0·258	..	10·0	..	33·6	..	..	..	61·6	..
4	..	0·240	..	13·5	..	35·3	..	..	..	58·3	..
5	2	0·227	0·228	10·0	30·0	36·6	37·1	10·0	11·0	56·3	63·0
6	..	0·209	..	15·1	..	37·8	..	..	..	61·0	..
7	..	0·196	..	12·1	..	39·3	..	8·6	..	56·0	..
..	3	..	0·190	..	30·0	..	42·7	..	7·7	..	46·0
8	..	0·183	..	13·0	..	40·0	..	..	..	57·0	..
9	..	0·171	..	13·0	..	40·6	..	..	..	54·8	..
10	4	0·159	0·157	13·8	31·7	41·4	46·0	10·0	7·25	60·6	54·5
11	..	0·147	..	14·5	..	42·6	..	..	..	53·7	..
12	..	0·135	..	15·6	..	45·2	..	..	..	45·0	..
13	5	0·125	0·128	14·1	40·0	46·4	52·6	10·0	7·2	50·0	48·5
14	..	0·115	..	15·2	..	46·4	..	..	..	49·0	..
15	..	0·107	..	13·5	..	47·0	..	10·0	..	51·0	..
..	6	..	0·102	..	36·4	..	55·5	..	4·1	..	47·5

The following figures, showing the elongation on different gauge lengths on a bar of armco iron annealed and hard drawn, are also of interest, and for the sake of comparison some of the other physical properties of these two samples are also tabulated.

TABLE 14

Showing effect of drawing on various physical properties of armco iron.

Reduction by cold drawing from 0·750 inch diameter to 0·437 inch diameter—*i.e.* 66 per cent. reduction in area without intermediate annealing.

Condition	*Maximum Stress Tons per square inch*	*Elongation per cent. on* $4\sqrt{Area}$	*1 in.*	*2 in.*	*10 in.*	*Reduction of Area per cent.*	*Brinell No.*	*Density*
Annealed .	20·8	63	75	55	19	69·5	92	7·872
Hard drawn .	44·0	9	12	7	2·6	24·4	220	7·855

Some figures showing how the elongation is affected by drawing patented steel with a sorbitic structure may also be given and may be compared with Goerens' results on high carbon steels, which were evidently not patented before drawing. In order to avoid the difficulty of gauge length and to make the tests more comparable with one another and with steels in general the final size of all the test-pieces was the same—viz. 1 centimetre. For the purpose five bars of medium carbon steel of the following composition,

Carbon	*Silicon*	*Manganese*	*Sulphur*	*Phosphorus*
0·50	0·13	0·65	0·037	0·039

$\frac{3}{4}$ inch in diameter, were drawn to various sizes, patented, and with the exception of the first test-piece then drawn to 0·450 inch diameter; the first test-piece being already reduced to that size was left in the patented condition. The results of the tests on these bars are given in Table 15.

TABLE 15

Original Diameter Inches	*Reduction in Area per cent. by Drawing*	*Maximum Stress Tons per square inch*	*Elongation per cent. on* $4\sqrt{Area}$	*Reduction of Area per cent. at Fracture*	*Izod Value in foot-lbs.*
0·450	*Nil*	60·8	21·2	51·0	20
0·490	14·0	67·4	13·1	43·7	7
0·550	32·7	71·0	12·5	42·6	8
0·620	47·3	78·9	12·5	42·9	8
0·680	56·2	78·6	13·7	46·2	32

After the first pass in drawing the elongation is reduced from 21 to 13 per cent. but is not further reduced even after 7 passes, a result which is in agreement with

Goerens' results on mild steels, and with the author's own results on armco iron. It is interesting to compare the physical properties of the hard-drawn armco iron bar in Table 14 with the last two test-pieces in Table 15. The sorbitic steel, although nearly double the strength of the armco iron, is yet distinctly more ductile.

The value of elongation as a ductility test for wire is extremely doubtful. It is true that the elongation falls suddenly when the wire is distinctly overdrawn, or of poor quality; but other tests, such as torsion and bending and reduction of area tests, show this equally well, if not better, and they are much more easily carried out.

Moreover, it is well known that blueing, and more particularly hot galvanising, increases the elongation greatly, and yet wire is very much more brittle after such treatment than it was before. The effect of blueing and hot galvanising is discussed in Chapter VII.

For certain specific purposes good elongation is no doubt important, and in such cases the maximum values have to be obtained by low temperature heat-treatment, but it should not be assumed that the properties of the wire in general are improved by such treatment.

REDUCTION IN AREA

The reduction in area at the fracture is a better test of the ductility of wire, and, although not usually measured in practical wire-testing, it forms a useful guide as to the point of maximum efficiency in drawing. The author found that in patented steel wire the percentage reduction in area actually increases with cold drawing up to a certain point and then begins to decline, until in overdrawn wire it is practically nil.

Some results will be found in the tables accompanying this chapter. He found that this point of maximum reduction in area coincided approximately with the best results in torsion tests, and it is highly probable that the elongation begins to decline seriously at the same point.

TORSION TEST

This test consists usually of twisting one end of a standard length of the wire—generally 100 times the diameter—while the other end is held rigid, until the test-piece fractures; the number of 360° twists withstood before fracture occurs is recorded and referred to as the torsion value. In one power-driven machine both ends are twisted in opposite directions.

The test is widely adopted in wire specifications, but unfortunately it is very open to misinterpretation unless the results obtained are coupled with a knowledge of its limitations and vagaries.

Thus, soft-drawn wire—*i.e.* lightly drawn mild steel or patented wire which has been reduced by drawing less than 70 per cent. reduction in area—twists locally and

a small portion only of the wire yields immediately, the twisting travelling gradually along it. This severely local yielding makes the test a very drastic one and the slightest flaw or hard spot in the wire may be sufficient to cause fracture before the bulk of the test-piece has been affected, so that figures varying from 2 or 3 torsions up to 70 on the same test-length may be obtained on the very same material. This does not necessarily mean that the wire is defective, since most wire passes through a stage in drawing where the torsion values are very variable; when drawn a little harder the same wire will twist in a regular manner and give the required number of torsions before fracture. Francis has published data showing the same effect with austenitic stainless steel wire. What it does indicate, however, is that its physical quality cannot be judged from the torsion test. With the exception of good mild steel which has been annealed or drawn only one pass, and medium carbon special acid steel patented and lightly drawn, no material can be expected to give consistently high torsion values when severe local twisting occurs.

The type of fracture is a very useful criterion of the quality of the wire. This is particularly applicable to wire which twists locally when, owing to the variability, the torsion figure is of little value. The fracture should be a straight shear through the cross-section, not a conchoidal break indicating splitting or longitudinal fracture.*

In the light of these remarks the following conclusions reached by some German and Swedish workers recently are of interest:

(1) If the surface of the wire is defective, unreliable results may be obtained.
(2) If the wire is underdrawn, uniform twisting over the whole of the test-piece will not be obtained.
(3) The test is not usefully applicable to all grades of wire.

Commenting on the factors, it may be said that the first is not objectionable but rather the reverse—though perhaps unduly severe on the wire manufacturer—since it tends to eliminate wire with a defective surface. The second factor has already been dealt with above, while the third can be controlled by using the test only where it is usefully applicable.

To the above factors the author might add a fourth, which is perhaps the most disturbing of all—viz. that reasonably good torsions can be obtained in wire which has been drawn just a little too far.

The author's experience leads him to the opinion that the torsion test when interpreted intelligently does provide a useful guide to the quality of wire.

With the limitations of the test in mind its significance can now be determined. It is clear that a really high-grade wire can be depended upon to give excellent results in the torsion test, and it may be considered established that any wire which stands consistently not less than 40 torsions in 100 diameters is first-class material for wire ropes and like purposes, provided, of course, that other requirements have

* Sometimes a wire gives a double fracture, especially when the number of twists is high. This second fracture is the result of recoil on the severely strained material, and is invariably conchoidal. Only the appearance of the primary fracture should be considered.

been met. But this is too high a standard for general use, since it would probably involve the rejection of about 70 per cent. of the wire produced daily.

The following standards for rope wire have been adopted in this country:

Tensile strength of wire in tons per square inch . .	80/90	90/100	95/105	100/110	105/115	110/120	115/125	120/130
Minimum torsions in 100 diameters .	34	34	33	32	31	30	29	28

On the Continent more faith is placed in the reverse bend test, and the standard for torsions, where there is one, is somewhat lower. In one Continental specification, for example, an *average torsion* of only 30 in 100 diameters is required.

Thus the torsion test as laid down in the above-mentioned British specification may be said to constitute a genuine safeguard against the acceptance of really bad wire, provided the test is conducted under the supervision of an inspector who has had some experience. Where the torsion test fails, where indeed any single specified test must of necessity fail, is in securing for the user the very best material that can be produced. Though this may be ultimately the function of a specification it is an ideal which neither the conditions of commerce and industry to-day nor our technical knowledge makes possible. All one can reasonably demand from most specifications at present is that they provide adequate safeguard against the use of seriously defective material.

BENDING TESTS

Direct bending tests have a certain appeal in that they offer a simple check on the ordinary ductility tests of elongation and reduction of area, and occasionally reveal surface defects not shown by the tensile tests. A direct bend test is, therefore, frequently specified for cold-drawn mild steel bars, and for wire a form of multiple bend test, consisting of wrapping the wire several times round its own diameter, is considered useful. In dealing with high tensile wire, the reverse bend test, in which the wire is bent backwards and forwards round a certain radius, is considered more useful. The radius used depends on the diameter of the wire, being generally some multiple of the latter. The wire is bent through an angle of 90° in one direction, then reversed through 180°, and so on until fracture occurs, the number of bends—excluding the initial 90° bend—before fracture being counted.

It may seem that this test is a very simple one to carry out, but experience has shown that several precautions must be taken and the conditions must be standardised if the results obtained by different operators are to be comparable. These conditions have been standardised in the bending machine put on the market by Messrs Bruntons, Musselburgh, and this machine has been recommended for use in this country by the Patent Steel Wire Association (see Frontispiece, B).

The following are the chief points to which attention has been paid in the construction of this machine:

Interchangeable radius dies and bushes make it possible to test all sizes 0·200 inch diameter and smaller on *one* machine.

Four sizes of radius dies are made as standard—namely, 2·5 mm., 5·0 mm., 7·5 mm., and 10·0 mm.—together with fourteen bushes accommodating all sizes of wire 0·200 inch diameter and thinner. Each bush is marked with the diameter of the hole and the radius die for which it is most suitable.

The distance from the bottom of the bushes which actuate the wire and the top of the radius dies can be varied.

The radius dies, which are in the form of hardened and ground steel cylinders mounted on detachable blocks, can be rotated if and when they become damaged, or may be entirely removed for check measurements.

Special guides in the vice ensure that the test-pieces are held vertically under the bending arm. This is very important if the test-piece is to be prevented from wriggling after two or three bends.

Both the jaws for gripping the wire move. This ensures that all diameters of wire are held centrally under the bending arm.

The frame and bending arm are of malleable iron and are practically indestructible.

The bending arm is supported at both ends, maintaining rigidity during long service.

For small wires a device is supplied for applying a predetermined tension before commencing the test. The advantage of this device is that the same tension can be applied in a series of tests.

The tension applied may be varied at will.

The bend test is perhaps even harder to interpret than the torsion test. It is certain that wire which is apparently brittle may sometimes stand this test well. For example, a steel wire containing 0·60 to 0·65 per cent. carbon was patented at 1000° C. and drawn from 0·432 inches to 0·149 inches diameter, a reduction in area of 88 per cent. This wire was exceptionally hard for its size, having a maximum stress of 134 tons per square inch and torsions nil, yet it stood reverse bending ten times round a radius of 3 diameters.

The bend test is a type of fatigue or endurance test under stresses so severe that rapid breakdown is inevitable. It has been criticised on the very ground that the rate of breakdown is far too rapid. Yet it is of interest to note some points of similarity between the results of fatigue endurance tests and those of the reverse bend test.

The author found that

(1) Both are influenced by the heat-treatment and microstructure of the wire, lead-cooled wire being superior to air-cooled wire in each.

(2) In the ordinary wire of commerce, which is decarburised, the amount of cold work, provided it is not excessive, has apparently little effect on either.

Other investigators in Germany and Sweden have also found this relationship, and more recently the work of Gill and Goodacre has helped to clarify this point, although, as they state, the relationship between the two tests is purely qualitative. The results obtained by these investigators are discussed at some length in the following chapter, but with regard to the bend test they state:

"The results obtained show that the number of bends for decarburised wire are higher than those for the corresponding wire drawn free from decarburisation. This is in accordance with the suggestion that the endurance properties of a decarburised wire are better.

" On the other hand, a comparison of the number of bends obtained on the 0·46 per cent. carbon wire air-cooled patented, with those on the 0·36 per cent. carbon lead-cooled patented steel, shows that the latter is distinctly superior; the fatigue endurance properties of the two materials, however, are practically the same, and possibly the former is superior. It would, therefore, appear that any relationship between the bend test and the fatigue limit is only qualitative."

Obviously the real significance and value of the bend test remains as yet obscure and the above investigators suggest the following alternatives:

(*a*) to increase the bending radius;
(*b*) to decrease the bending deflection and so modify the test to bring it into line with the test expounded by Arnold many years ago.

All this presupposes that a test of the endurance under stresses well above the limiting fatigue stress is of any value at all, a point which many doubt.

Taking the test as it now stands, the following empirical formula was worked out by the author as an indication of the bends which rope wire should stand :

$$N = \frac{\frac{\pi}{2} R^2}{d^2}$$

where

N = the number of reverse bends;
R = the bending radii in millimetres;
d = the wire diameter in millimetres.

And with the bending radii 2·5, 5, and 10 millimetres, diameters being plotted as ordinates, and the values of N as abscissæ, the parabolic curve in Fig. 53 is obtained from which values for N are obtained similar to those required in B.S.I. specifications for rope wire.

Notched Bar Impact Tests.—This form of test cannot for obvious reasons be applied to wire unless in some modified form.

Tests carried out some years ago on bars containing 0·50 per cent. carbon showed that one severely drawn bar had an Izod value of over 30 foot-lbs., with a tensile

strength of 78·6 tons per square inch. This unexpected result was considered at the time to be due to some accidental cause, since other bars similarly heat-treated but less severely drawn gave very poor Izod values. The details of these early tests are given in Table 15.

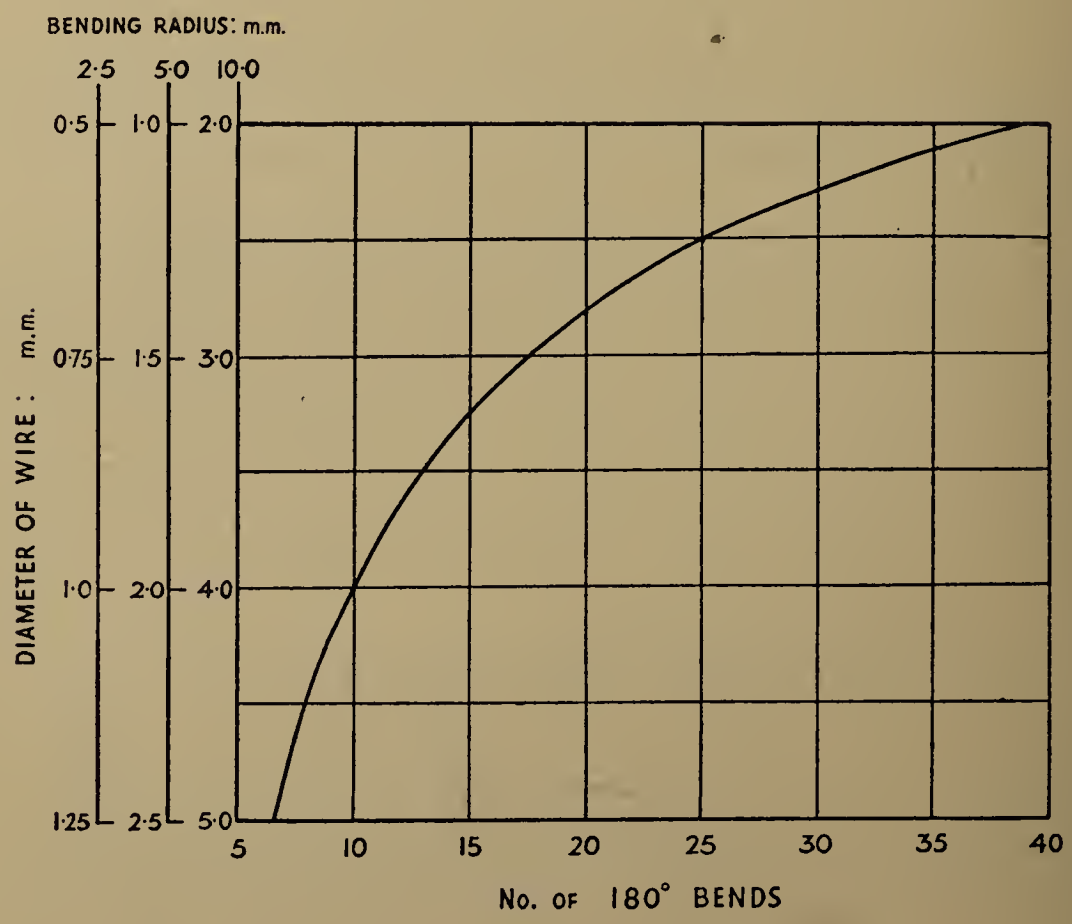

FIG. 53

Later on Brown in conducting tests on cold-drawn mild steels found that the more heavily drawn bars gave higher Izod values than the lightly drawn bars (Table 16).

A more extended investigation was recently undertaken by the author and the results obtained are important. The following steels were used:

Description	*Carbon*	*Silicon*	*Manganese*	*Sulphur*	*Phosphorus*
	per cent.	per cent.	per cent.	per cent.	per cent.
A—Basic O.H. Steel	0·430	0·160	0·630	0·034	0·015
B—Basic O.H. Steel	0·350	0·075	0·810	0·045	0·034
C—Acid O.H. Steel .	0·460	0·250	0·400	0·015	0·016
D—Acid O.H. Steel .	0·320	0·290	0·250	0·022	0·016
E—Acid O.H. Steel .	0·300	0·290	0·430	0·028	0·012

All the Izod tests were carried out on bars which had been patented, cooled in lead, and drawn. In the cases of steels A and C all test-pieces were prepared from bars drawn to 0·450 inch diameter from various original diameters, while those from steels B, D, and E were machined from bars drawn from the same original diameter to various finished sizes as indicated in Table 17.

The values obtained for maximum stress, elongation, and contraction are also recorded in the tables.

These results have been recorded in full because it is considered they are extremely important. That they are not accidental or exceptional is indicated by the fact that they were anticipated by earlier results and were deliberately sought for in a particular way.

The high Izod values obtained when these steels are drawn to the extent of not less than 55 per cent. reduction in area indicates great toughness across the fibre, and suggests that the toughness of suitably patented and drawn medium carbon steel rope wire, if it could be estimated in terms of an Izod test, would be extremely high. It is well known that ageing and mild blueing tend to reduce this toughness, and it was therefore thought desirable to determine the extent of the effect in some of the above specimens. The following results were obtained after blueing:

Steel "B"—0·450 inch Diameter Bar

	Izod Values
As drawn	60–53–55
After blueing	31–74–41

Steel "D"—0·450 inch Diameter Bar

Aged one month, and blued.

	Izod Values
As drawn	41–25–30
Aged and blued	29–31–31

Steel "E"—0·450 inch Diameter Bar

	Izod Values
As drawn	28–25–25
Aged and blued	41–36–37

TABLE 16 (BROWN)

Series	Reduction of Area per cent.	Interval between Drawing and Testing	Young's Modulus Tons per square in.	Limit of Proportionality Tons per square in.	Yield Stress Tons per square in.	Ultimate Strength Tons per square in.	Elongation per cent. on $4\sqrt{area}$	Reduction of Area per cent.	Hysteresis Inches on 4-in. Gauge Length	Izod foot-lbs.
A	Annealed Bar		13,390	10·52	14·15	24·93	43·83	67·50	·000057	99·34
B	8·7	1 hour	13,350	3·87 4·74	23·14	26·69	36·80	70·84	·000336	47·5
		1 day	13,460	7·23 11·57	24·09	27·51	26·44	68·31	·000112	43·3
		8 days	13,480	12·35	26·38	28·85	28·30	67·48	·000128	32·1
		28 days	13,500	14·77	27·65	29·90	25·15	67·56	·000088	19·8
		223 days	13,400	14·68	27·62	30·69	25·15	65·33	·000064	16·3
C	19·94	1 hour	12,720	4·39	..	..	..	..	·000176	22·6
		1 day	13,050	4·84	30·19	32·25	17·60	60·91	·000100	12·3
		6 days	..	..	32·73	35·33	17·61	57·27	..	..
		8 days	13,210	6·69	32·73	35·13	18·24	56·99	·000076	7·0
		28 days	13,230	9·12	32·17	35·33	21·07	59·07	·00012	6·4
		219 days	13,270	11·04	32·25	35·75	20·75	53·96	·000040	6·57
D	28·02	1 hour	12,520	4·63 5·73	29·33	33·24	22·02	62·23	·000324	9·2
		2 days	12,740	5·42 6·46	31·60	34·14	22·02	60·68	·00016	5·2
		7 days	13,070	10·49	33·30	35·50	18·87	62·03	·00016	4·8
		24 days	13,020	11·79	35·27	37·89	15·72	56·98	·000128	4·3
		216 days	13,280	13·09	35·46	37·45	18·87	58·03	·000036	4·9

E	35·51	1 hour	13,010	3·54 6·40	34·43	37·39	20·75	60·52	·000272	13·7
		1 day	13,220	7·33 9·63	36·40	38·00	16·98	61·28	·000128	10·85
		7 days	13,230	12·36	38·66	41·59	22·64	59·75	·00020	6·9
		25 days	13·200	16·08	38·94	41·06	15·10	55·50	·000064	7·49
		187 days	13·360	17·01	40·63	42·13	18·56	54·67	·000055	17·73
F	41·95	1 hour	12,600	5·14 7·62	34·70	37·61	18·87	55·63	·00024	7·32
		1 day	13,020	7·57 10·27	36·12	38·60	18·24	62·22	·00022	6·78
		7 days	13,020	10·16	38·66	40·95	15·10	56·59	·00024	4·07
		26 days	13,140	14·05	39·50	40·98	13·84	50·46	·00012	5·00
		188 days	13,220	15·08	41·20	42·75	13·84	50·46	·000048	7·47
G	48·15	1 hour	12,910	4·37 6·78	36·67	39·50	19·50	58·37	·00033	17·5
		1 day	13,250	8·34 12·22	38·37	40·86	15·10	56·56	·000248	12·2
		7 days	13,270	12·58	41·20	41·78	13·20	50·87	·000112	11·5
		27 days	13,280	15·32	42·05	42·88	13·84	51·86	·000096	11·91
		188 days	13·280	16·91	42·88	43·81	13·20	49·76	·000048	11·63
H	52·98	1 hour	12,830	5·30 8·35	38·66	41·40	16·35	50·63	·00029	26·9
		1 day	13,250	6·77 10·77	38·94	41·34	15·72	51·28	·000144	13·1
		7 days	13·200	11·91	42·29	43·17	12·58	47·86	·00008	7·5
		28 days	13,150	14·98	42·33	43·53	12·89	48·37	·00008	8·69
		190 days	13,320	15·06	42·88	44·16	13·20	48·99	·000048	10·3
I	57·45	1 hour	12,710	5·35 8·13	38·94	40·18	13·55	49·20	·000216	32·6
		1 day	13,250	5·69 10·16	41·30	43·76	14·29	49·80	·00016	29·12
		7 days	13,190	10·97	43·17	43·73	12·58	51·40	·000144	13·87
		26 days	..	..	..	..	..	..	..	18·82
		191 days	13,260	14·61	44·90	45·46	11·73	47·26	·000044	..

TABLE 17

Tables showing Effect of Cold Work on the Izod Value of Patented Steel

No. of Passes	Original Diameter Inches	Final Diameter Inches	Reduction in area by Drawing per cent.	Maximum Stress Tons/sq. in.	Elongation per cent. $4\sqrt{Area}$	Contraction of Area per cent.	Izod Value in ft.-lbs.
				Steel "A"			
3	0·530	0·450	28·0	65·0	13·1	43	5–5–5
4	0·5625	0·450	36·5	65·0	12·5	39	6–7–6
5	0·594	0·450	43·0	66·6	12·5	36	5–8–7
6	0·625	0·450	48·5	68·5	11·3	35	8–8–9
8	0·6875	0·450	57·0	74·0	11·2	35	33–30–48
9	0·750	0·450	64·0	74·6	9·4	27	41–43–41
				Steel "B"			
Original bar 15/16″ diameter, patented, lead cooled, and drawn to 5/8″, 9/16″, 1/2″, and 0·450″.							
..	15/16	0·620	56	65·5	11·5	36	29–35–28
..	15/16	0·569	63	66·0	11·5	34	25–34–32
..	15/16	0·4965	72	70·0	11·25	30	55–45–66
..	15/16	0·448	77	71·5	10·0	30	60–53–55
				Steel "C"			
1	0·460	0·450	5	49·8	15·0	36	18–18–19
2	1/2	0·450	20	58·8	11·2	34	6– 6– 6
3	9/16	0·450	36	67·0	11·9	35	11–12–11
4	11/16	0·450	57	70·6	11·2	35	31–23–26
5	3/4	0·450	64	74·6	10·0	25	25–32–28
6	13/16	0·450	70	77·0	10·0	25	28–40–29
				Steel "D"			
Original bar 13/16″ diameter, patented, lead cooled, and drawn to 5/8″, 9/16″, 1/2″, and 0·450″.							
..	13/16	0·625	40	54·0	13·0	44	17–16–16
..	13/16	0·567	52	55·3	13·0	39	19–19–23
..	13/16	0·500	62	56·8	11·9	33	24–23–22
..	13/16	0·447	70	60·8	10·1	33	41–25–30
				Steel "E"			
Tested as steel "D."							
..	13/16	0·623	41	53·6	14·5	47	25–23–22
..	13/16	0·567	52	54·0	14·0	41	25–27–22
..	13/16	0·500	62	56·8	13·0	38	32–24–21
..	13/16	0·447	70	60·2	10·1	33	28–25–25

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[2] Boynton, "The Hardness of the Constituents of Iron and Steel," *Journal of the Iron and Steel Institute*, 1906, No. 2, p. 142.

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[4] Bolton, *Institute of Metals Journal*, 1911, vol. xi., p. 188.

[5] Longmuir, "Some Aspects of Wire-Drawing," *Journal of the Iron and Steel Institute*, 1912, No. 2.

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CHAPTER VI

EFFECT OF COLD WORK ON THE PHYSICAL PROPERTIES OF METALS—*continued*

THE ELASTIC PROPERTIES

A GREAT deal of confusion has arisen regarding the terms "elastic limit," "limit of proportionality" and "yield point," and it is not always clear what is meant when these terms are used. In annealed mild steel these points are well defined,

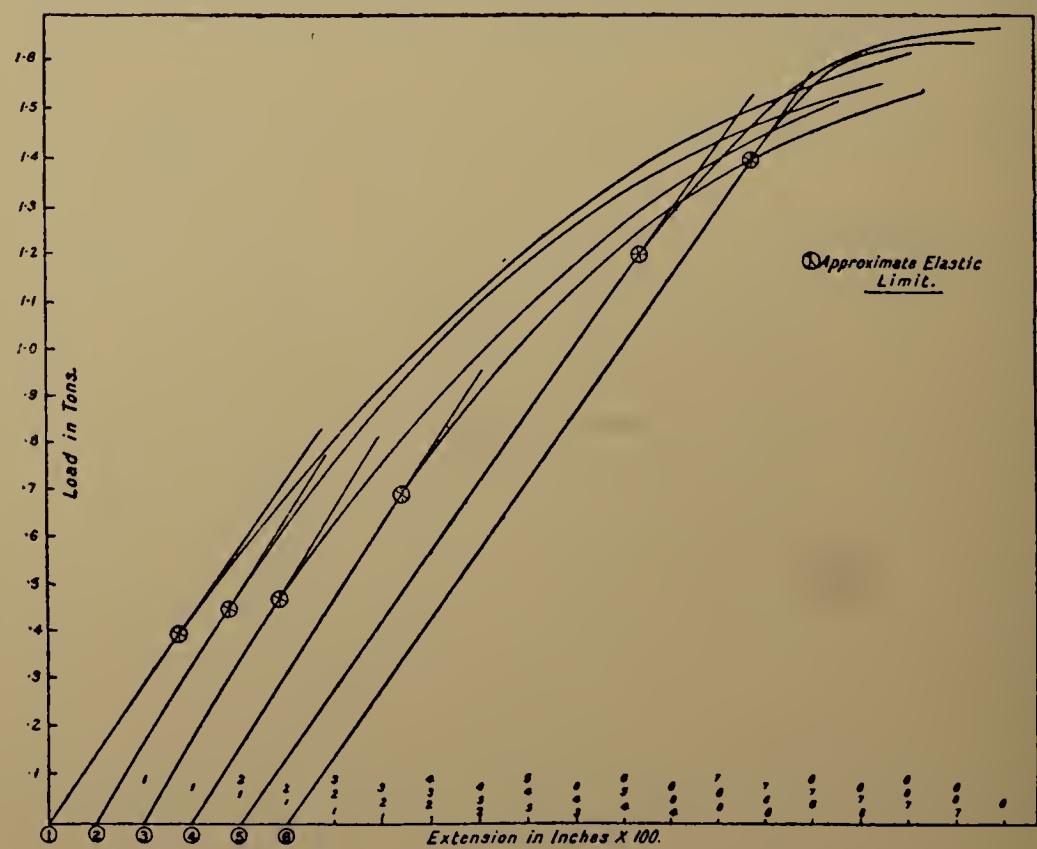


FIG. 54

the first two coinciding and the last occurring, as a rule, at a slightly higher load. In high tensile steel, and particularly in hard-drawn wire, these points are not well defined, and there is a tendency to depart from the strict meaning of the terms. For this there is some justification in that they have their origin in mild structural steels, and are only really satisfactory when applied to them.

When specimens of ductile metals are tested with the extensometer shortly after rolling or drawing, and the extensions plotted against loads up to that point where a distinct permanent yield occurs, it is found that the resulting "curve"

departs from the straight at very low loads; in fact, it is probably never truly a straight-line diagram. This slight curving was at first attributed to errors in measurement due to the straightening out of kinks or bends often found in wire and strip specimens. That there is a definite and almost immediate departure from perfect proportionality of stress and strain, quite apart from any slight errors due to the above causes, has now been definitely established by several investigators. Moreover, the fact is fully confirmed by comparing such curves as those illustrated in Fig. 54.

These tests were made on wires first drawn to $\frac{1}{4}$ inch diameter and then rolled to a sectional area of 0·0249 square inch. All the specimens were taken from the same length of wire; all the heat-treatment was carried out within a few hours of rolling, and one-half of the set was tested within a week of rolling, the other half was allowed to age for six months. The temperatures chosen for heat-treatment were 100° and 350° C. The extensions in the tensile tests were measured by means of an extensometer capable of being read to one ten-thousandth of an inch.

No.	*Treatment*	*Area in Inches*	*Elastic Limit in Tons per square inch*	*Modulus in Tons per square inch*	*Breaking Load in Tons per square inch*	*Bends*	*Elastic Limit Extension per cent. on 10 inches*
1	As rolled . . .	0·0249	16	11,700	70·7	29	0·137
2	Aged 6 months . .	0·0249	18	13,140	71·0	28·5	0·137
3	Heated to 100° C. .	0·0249	19	13,570	71·0	28·1	0·140
4	Heated to 100° C. and aged 6 months .	0·0249	28	12,700	69·2	26	0·220
5	Heated to 350 C. .	0·0249	48	11,500	72·0	23	0·420
6	Heated to 350° C. and aged 6 months .	0·0249	56	12,700	70·0	21	0·44

Although figures have been given for the elastic limit and modulus of elasticity, these cannot be taken as strictly accurate in all cases, because in the first curve at least there is probably no straight portion at all. Bend tests were made on these wires, the results of which will be referred to later.

The chemical composition of the wire tested as described above was:

Carbon	0·42 per cent.
Silicon	0·17 ,,
Manganese	0·73 ,,
Sulphur	0·033 ,,
Phosphorus	0·029 ,,

Similar conditions, however, have been found in cold-drawn and rolled mild steels, and also in cold-worked non-ferrous metals.

From these and many other confirmatory tests by other investigators it may be concluded that heat-treatment and ageing after cold work have a very pronounced effect on the elastic properties, and it would seem that the effect of ageing is actually greater after heat-treatment than before. Even after boiling followed by ageing, however, the elastic limit of the steel wire used in the experiments quoted above is only about 40 per cent. of the ultimate load; while it rises to 80 per cent. after heating at 350° C. and ageing six months. It is this condition of maximum elasticity which really represents the climax of the hardening effect of cold work, and this has now been recognised in drawing up many specifications for cold-worked material where a high elastic limit or "proof stress" is desired.

It is generally claimed by manufacturers that cold working increases the elastic limit of the material. As we have seen above, this is not strictly true unless the metal has been heated to a moderate temperature after cold work. If, however, we substitute the terms "yield point" or "proof stress" for elastic limit, and stipulate a definite amount of permanent extension which must not be exceeded, then the statement holds good. Indeed, the total extension at the breaking load in a high tensile wire is so small that for many purposes it may be considered elastic almost up to the limit of its strength.

The effect of cold work on the elastic properties has been studied by different authorities, and many conflicting statements have been made on this subject. Research has, fortunately, cleared up this matter in such a way as to explain the apparent contradictions of the earlier results. In order to make the matter clear it would be well to consider some of the causes of the discrepancies in the results above mentioned.

(1) Slight deviations from perfect proportionality of stress and strain have been ignored by some investigators, and high values, which are more truly described as the yield point or proof load, have been called the elastic limit. To avoid further confusion it may be stated that by the term "elastic limit" is here meant the limit of proportionality of stress and strain.

(2) The method of applying cold working has not hitherto been considered sufficiently, and attempts have been made to reconcile values obtained by direct straining in tension with those obtained by cold drawing.

(3) The effects of ageing and mild "blueing" were not sufficiently considered by the earlier workers, although we now know the limit of proportionality is profoundly influenced by both.

(4) Arising out of (3) the effects of ageing are greater in some metals than in others—*e.g.* ingot iron appears to recover very quickly from the temporary effects of strain, and mild steels, in general, are probably more quickly stabilised after cold work than high carbon steels.

In view of these facts, now established, it is not surprising that confusion has arisen in the past, and even still exists, regarding the effect of cold working on the elastic properties. Great stress was laid by metallurgists on the importance of the limit of proportionality, particularly in material which would be subjected to re-

peated stress reversals, since it was assumed, not unnaturally, that once this limit was surpassed fatigue would set in. Curiously enough it is research on the subject of fatigue that has led to a truer appreciation of the significance of the limit of proportionality, and, as is not infrequently the case, practical experience had already proved to the engineer what research has now discovered and explained—viz. that the limit of proportionality in a metal is more or less accidental and very largely dependent on the state of internal stresses. The author was once informed by an engineer, whose speciality was steam turbines, that he had been particularly advised against the use of a certain alloy for turbine blading because of its low limit of proportionality. This advice he disregarded, with beneficial results.

Most of the early workers stated that direct straining in tension lowered the elastic limit in compression, and it was assumed that cold work in general had this effect. It has been shown, however, by Aitchison,[1] and also by Merrils,[2] that the elastic limit in compression is greater in cold-worked metals, such as wire, than it is in tension. This fact, instead of contradicting the earlier work, as might at first sight be supposed, really confirms it, since practical cold-working operations deform the metal by compression and leave it in a state of internal tension, while direct straining in tension has the opposite effect. It is therefore quite natural that the limit of proportionality in wire and strip should be higher in compression than in tension.

Summing up, we find that cold work has a profound effect on the elastic properties of metals. It produces in the metal a condition of imperfect elasticity. This condition, however, is not stable, and there is a tendency to return to the truly elastic state with time—a tendency which is greatly accelerated by heating to comparatively low temperatures. The temperature at which maximum elasticity is reached naturally varies in different alloys; in steel it appears to be about 375° C. After heating to this temperature cold-worked steel has a very much higher elastic limit than when in the "normalised" condition. The modulus of elasticity is also slightly affected, as may be seen from Fig. 54.

Since the amount of extension at given loads in wire is a matter of considerable importance, it is interesting to compare points at the same stress in the first and last curves in Fig. 54. In the first curve, although 1·35 tons marks a point far above the true limit of proportionality, the total extension at that load is only 0·635 per cent.; while in the last curve at the same load, which in this case is the true limit of proportionality, the total extension is 0·485 per cent. Since the modulus in the two cases is approximately equal, it may be assumed that the difference between these two extensions—viz. 0·150 per cent.—represents, roughly, the amount of permanent set in the first case at a load of about 80 per cent. of the maximum stress. It will thus be evident that when static loads only are involved, the low value of the limit of proportionality of cold-worked material is not a very serious matter.

If we regard the elastic properties entirely from the static point of view we are not greatly concerned with slight deviations from the straight line in the stress-strain diagram. The engineer is mainly concerned with Young's modulus and with the elastic stretch. As long as this stretch is below a certain value, at a certain

load, it is not a matter of great importance whether this load is truly a limit of proportionality or not. In order to avoid confusion, therefore, the practice has grown up of stipulating a certain small extension, which must not be exceeded at a certain load, and in order to designate this point clearly it is called the "proof-stress" instead of the yield point or elastic limit. This avoids any ambiguity in specifications, and is being largely adopted in regard to cold-worked steels, and, indeed, to high tensile steels in general.

When the material is subjected to alternating or pulsating stresses, however, the question of "fatigue" arises, and we have to consider what bearing the lack of perfect proportionality of stress and strain has on this question. The slight permanent set which occurs at very low stresses in cold-worked steels suggests a certain degree of mobility in the metal, such as is found in extremely viscous fluids. A similar condition, however, is found in some annealed metals—such as copper, brasses, and in some heat-treated steels. Different explanations of this imperfect elasticity have been presented. When a piece of metal is stressed, yield does not occur in all crystals simultaneously, but occurs first in one or two specially situated, so that shear takes place on the 45° plane. This makes the true elastic limit difficult to determine, and makes it depend to a great extent on the sensitivity of the measuring instrument. Tammann [3] has used the method of observing the first signs of slip to determine the elastic limit and obtained very low values, as the following results show:

	Elastic Limit by Slip	*Elastic Limit by Extensometer*
Copper cast and slowly cooled . .	203 kg./cm.^{2}	2780
Iron strongly annealed . . .	2370 ,,	5900
Nickel heated 1 hour at 1350° C. . .	788 ,,	5570

Professor Jenkin has offered a further explanation of the slip in certain crystal units at very low stresses.

Arguing from a study of simple models he suggests that it is purely an accidental condition due to certain of the crystal units being under initial stresses, so that slip occurs in these when a slight additional load is put on, thus causing minute yielding of the test-piece and a slight departure from the proportionality of stress and strain. This condition, he showed by his model, could be removed by submitting it to alternating stresses of sufficient magnitude to bring all the units into the "stress-free" condition. Acting on this hypothesis Gough found that copper could be restored to the elastic condition by previously applying alternating stresses. It would therefore be a matter of considerable interest to find if cold-worked metals could be restored to the elastic condition by similar methods. This idea of certain crystal units being in a state of stress seems particularly applicable to metals in the cold-worked condition, since some of the crystals must be left just on the point of slipping after the last application of cold work, and a very slight additional load only would be sufficient to cause slip; hence the low elastic limit. This hypothesis also affords an explanation of the recovery of elasticity by ageing and mild blueing,

which might be expected to release the internal stresses. In Fig. 55, reproduced from a paper by Merrils,[2] are some stress-strain diagrams of the same piece of cold-worked metal before and after the application of alternating stresses, which seem to prove that Professor Jenkin's theory also applies to cold-worked material. On the other hand, Aitchison [1] has shown that if excessive loading is applied in this way the limit of proportionality is decreased instead of increased.

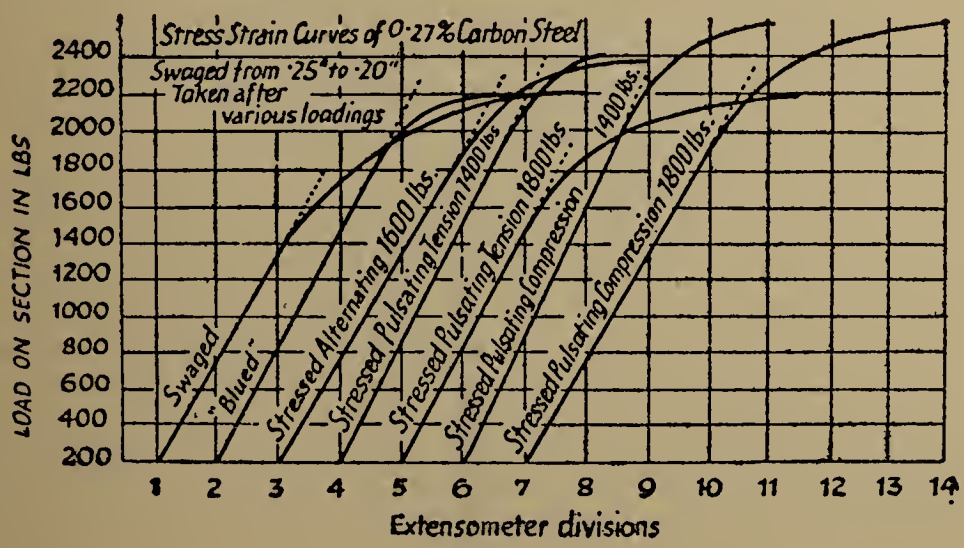


Fig. 55

From a study of the more recent work on the subject then, it may be taken as almost definitely established that the typically low limit of proportionality in cold-worked metals is due to a state of mechanical instability depending on the internal stresses. Ageing and blueing stabilises the metal more or less by removing the internal stresses, but the metal may also be stabilised by the application of properly controlled alternating stresses. Whether it is advisable to stabilise all cold-worked metal by blueing or not is a point which is discussed in the next chapter, which deals with the effect of heat-treatment after cold work.

FATIGUE

Although possibly related to the elastic properties of individual crystalline units, the fatigue limit is quite independent of the elastic limit of the metal aggregate. The latter, it has been shown, is more or less accidental, depending on the state of the internal stress in a metal as well as on several other factors. Yet the limiting fatigue stress even though it cannot be co-related to the limit of elasticity is, nevertheless, analogous to it. The limiting fatigue stress might be regarded as the elastic limit under repeated stresses. Just as in earlier days some investigators tended to place undue emphasis on the importance of the elastic limit, so to-day the same tendency is apparent with regard to the fatigue limit. The truth is that its importance, relative to that of other physical properties in wire as in other forms of metal, varies according to the particular duty the wire has to perform. In the wires of a guy rope where the load, but for slight vibration caused by the wind, is static, the

actual fatigue limit is of no significance, except in so far as it may possibly throw some light on the general properties of the wire; in a haulage rope its importance is doubtful; but in the ropes of the paravane used in mine sweeping the fatigue limit of the wire *in sea water* is the supremely important point.

Until the advent of machines specially designed for the fatigue testing of wire, it was not easy to estimate very fully the effect of severe cold working on the fatigue limits. In testing wire it is of prime importance that the skin be not removed by machining, etc. Elaborate methods of affixing suitable ends have been described by Lea and Dick [4] and by Goodacre, [5] and recently special machines have been constructed to overcome this difficulty.

Since most of the results given in this chapter have been carried out on the Haigh-Robertson machine a brief description of this may be advisable here. It represents a new departure in fatigue testing, and is based upon the principle of a rotating strut, to which the well-known Euler theorem is directly applicable (see Frontispiece, A).

The maximum stress on the wire occurs at mid-length, so that fracture always takes place at or near this point.

The wire under test is held at one end in a chuck fitted to an electric motor spindle, and at the other end in a holder carrying a special thrust bearing. An important feature of the machine is that the wire requires no preparation; it is only necessary to point the one end to fit a small tapered sleeve which runs in the bearing. The length of the wire is bowed out by end-thrust into the form of a curve, and is simultaneously caused to rotate at high speed by the electric motor. Eventually, after a number of revolutions dependent upon the stress, the wire breaks at or very near the centre of its length—the position of maximum stress.

The stress calculation is made on the angle of inclination and not on the deflection at the centre of the strut—as was the case with the original machine—by the application of the Euler theorem.

The angle of deflection is measured by a vernier and angular scale attached to a swinging headstock, and the limiting fatigue stress can be determined accurately to $\pm 0{\cdot}1$ ton per square inch.

Another important feature of the machine is the rapidity with which the tests can be carried out. The customary speed is about 14,000 stress cycles per minute, or 20,000,000 stress repetitions in 24 hours. It is therefore quite possible to obtain data for a full S/N curve in 24 hours; this includes an overnight run of some 15 to 20 million stress reversals.

Before passing on to the results obtained on this machine it may be well to summarise briefly some of the earlier results obtained on the Wöhler and the Haigh machines. A few of these collected from various sources are tabulated opposite. They show that the fatigue limit is quite definitely increased by cold drawing, though not at all in the same proportion as the tensile strength.

Although they give some idea of the fatigue limit which may be expected in bright-drawn bars, of the value of this limit in high tensile wire as used for ropes and springs they give little or none.

Fortunately some definite information on this point, both as regards bending and torsional stresses, is now available from the work of Lea and his co-workers, Gill and Goodacre and others, but much work remains to be done in this field. That surface condition has a profound effect on the fatigue properties of a material has been recognised for some years, the pioneer work in this country having been carried

Steel	*Condition*	*Maximum stress in Tons per square inch*	*Limiting Fatigue Stress in Tons per square inch*	*Ratio* $\frac{L.F.R.}{M.S.}$	*Source and Machine*
Armco iron	Annealed	20·3	±9·75	0·96	Merrils on Haigh machine
,,	Hard drawn	39·4	±17·75	0·90	,,
0·26 carbon	Lightly drawn	40·8	±19·1	0·94	Aitchison on Wöhler machine
0·29 carbon	Annealed	32·3	±15·4	0·95	Brown on Wöhler machine
,,	,,	32·3	±12·35	0·77	On Haigh machine
,,	Hard drawn	56·0	±20·8	0·75	On Wöhler machine
,,	,,	56·0	±19·8	0·71	On Haigh machine
0·45 carbon	Patented and drawn	71·5	±21·25	0·60	Author on Haigh machine
0·66 carbon	Drawn	60·6	±24·0	0·79	Aitchison on Wöhler machine
0·75 carbon	Patented and drawn	95·0	±32·5	0·68	Author on Haigh machine
,,	Annealed 600° C. after drawing	65·0	±31·0	0·95	,,

out by Lea and his assistants in respect of wire [6] and Hankins and his co-workers [7] in the case of leaf springs. The true effect of wire-drawing on these properties can, therefore, be demonstrated only by tests on wire in which the carbon content of the surface is equal to that of the interior. Now, in the ordinary wire of commerce, this condition is seldom attained because decarburisation in some degree is almost inevitable, and it is therefore important from the practical viewpoint to study this aspect of the question. Probably the most satisfactory method of dealing with the matter will be to study the effect of wire-drawing on material free from decarburisation in the first instance and then to consider how this is modified by practical

considerations. The recording of fatigue tests involves the printing of such a mass of figures that it can scarcely be done in detail even in a technical paper, much less

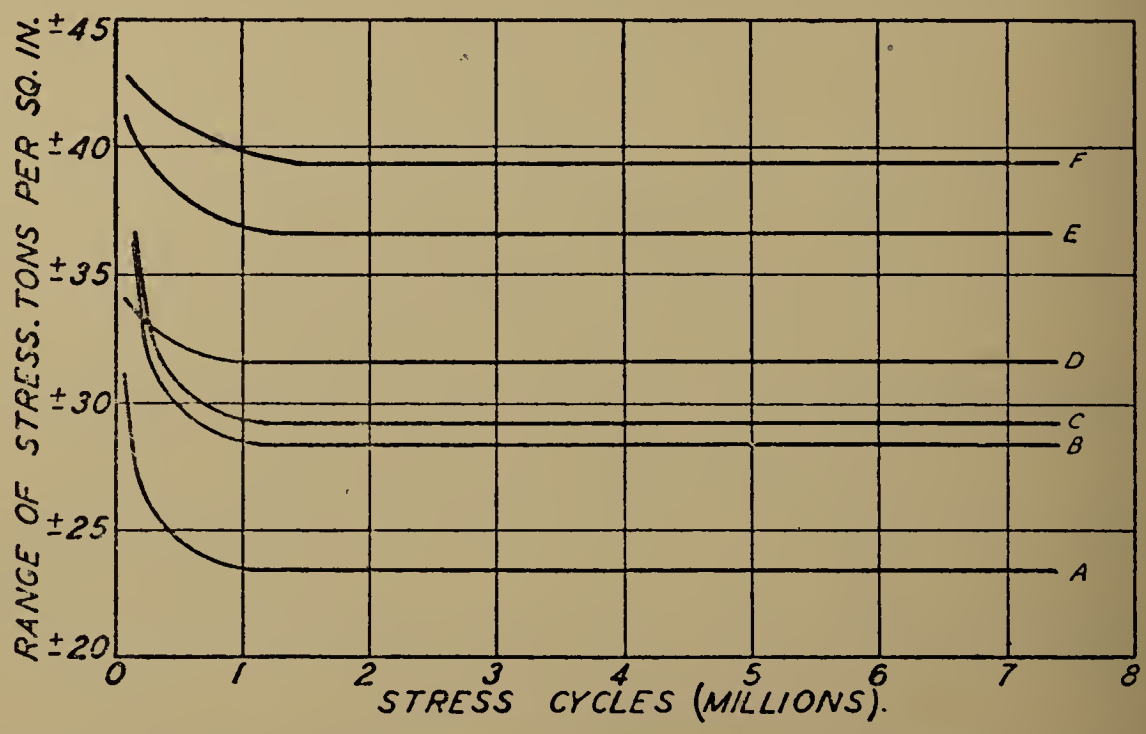


FIG. 56.—The Effect of Surface Condition on 0·79 per cent. Carbon Lead-Cooled Patented Wire.

A. Drawn from decarburised rod. *B*. Same but machine polished. *C*. Same but polished to 000 Fortin emery. *D*. Drawn from rod free from decarburisation. *E*. Same as *D* but machine polished. *F*. Same as *D* but polished to 000 Fortin emery.
A, *B*, and *C*. 75 per cent. reduction. *D*, *E*, and *F*. 72·5 per cent. reduction.

in a text-book. It is possible here to state only the final results and conclusions reached by different investigators. From the work of Gill and Goodacre the following points emerge:

(1) The effect of the carbon content is completely obscured by the decarburised surface, especially for the higher percentage reductions.

Within a carbon range of 0·36 per cent. to 0·79 per cent. the increase in the patented condition is of the order of ±2 tons per square inch only.

While with wire reduced 80 per cent. reduction in area the increase due to carbon is practically negligible, being only ±1 ton per square inch.

(2) When the decarburised skin has been removed before drawing, the increase is as follows:

	Reduction in Area per cent. by Drawing				
Carbon	25	50	75	80	85
	Limiting Fatigue Stress in Tons per square inch				
0·36	±22·3	±25·9	±29·9	±29·8	±31·4
0·55	±26·4	±28·7	±30·8	±32·0	±32·6
0·79	±26·8	±31·8	±34·8	±35·0	±35·7

Somewhat higher results have since been obtained with wire containing 0·85 per cent. carbon, drawn to 85 per cent. reduction, further reduction in the same wire causing a decrease.

(3) The effect that the surface condition of the wire has upon the fatigue properties is well illustrated in Fig. 56, and the results recorded therein are in accord with those obtained by Lea and Dick working on the torsional fatigue properties of similar wire when the ratio is

$$\text{Tensional fatigue range} = \tfrac{3}{2} \times \text{torsional fatigue range.}$$

Summarising the effects of the various factors influencing the fatigue limit of wire:

(1) Owing to the presence of a decarburised envelope the fatigue limit of the ordinary wire of commerce is for all practical purposes unaffected by the carbon content.

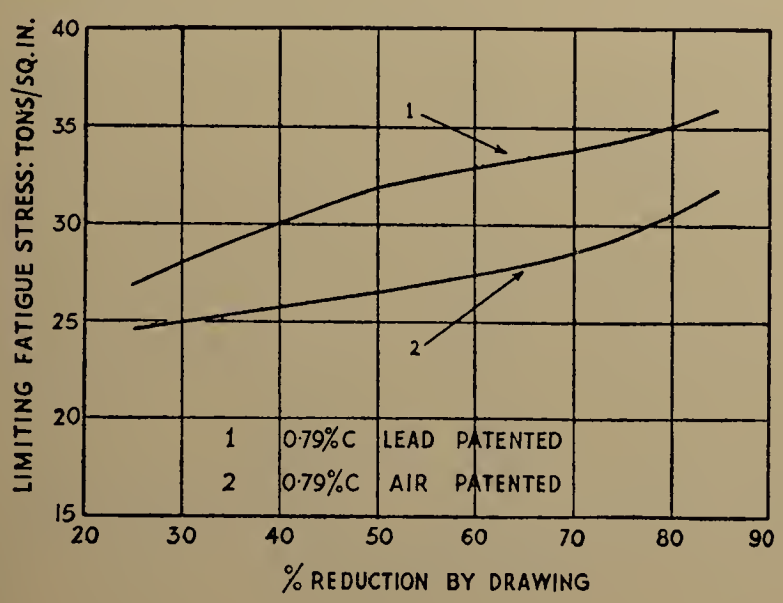


Fig. 57

(2) It is increased by drawing to the extent of about ±5 tons per square inch only in decarburised wire, and by about ±10 tons per square inch in wire free from decarburisation.

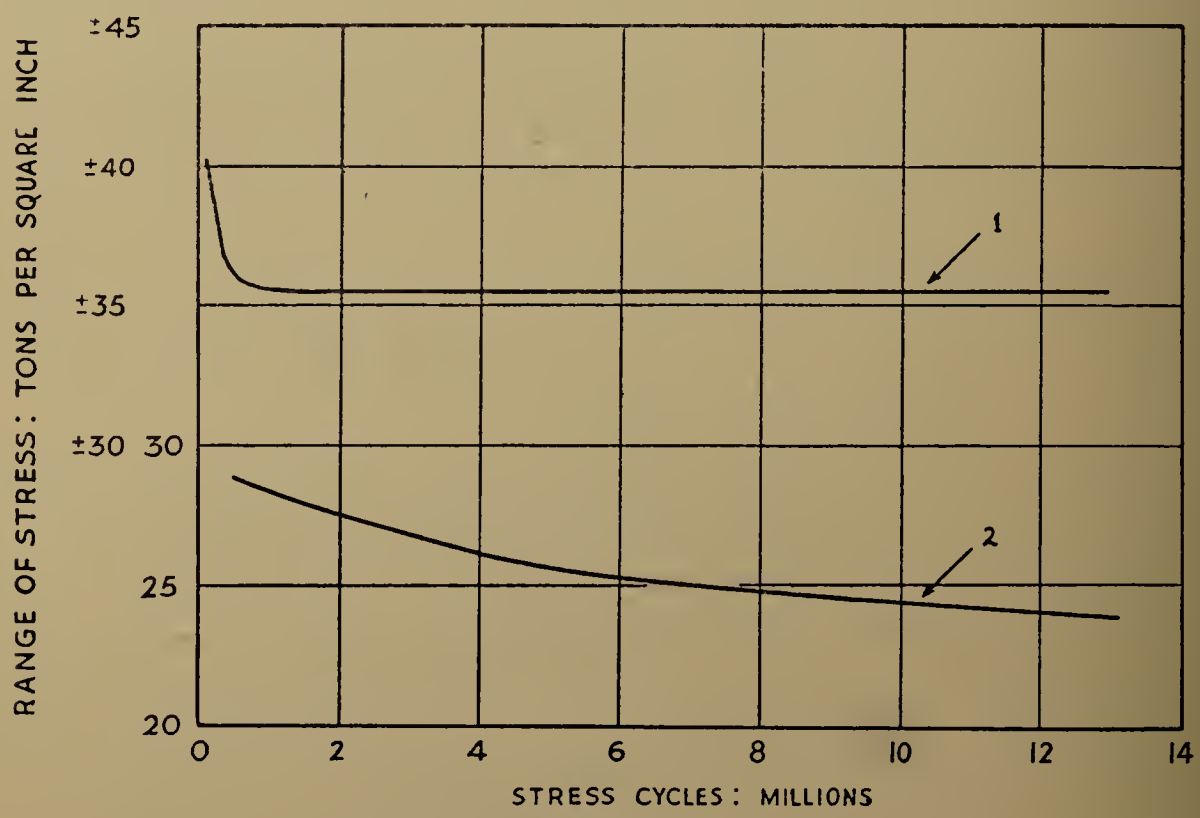
(3) Polishing the wire may add ±8 tons per square inch.

(4) The fatigue limit of lead-cooled patented wire is higher than that of air-cooled wire. Thus the fatigue limit of 0·36 per cent. carbon steel wire lead cooled is on the average about ±3 tons per square inch higher than that of 0·46 per cent. carbon steel wire air cooled when both are free from decarburisation.

In 0·79 per cent. carbon steel the fatigue limit of lead-cooled wire is on the average ±5 tons per square inch higher than that of air-cooled wire when both are free from decarburisation (Fig. 57).

In the ordinary wire of commerce, however, the effect of lead cooling is almost obscured by the decarburised layer.

(5) There are indications of a mass effect on the fatigue limit of wires. Thus in a wire of 0·036 inch diameter containing 0·76 per cent. carbon, with a tensile strength of 135 tons per square inch, drawn without any special precautions regarding removal of decarburisation, a value of ±40 tons per square inch was obtained, which is equal to that of a wire 0·80 inch diameter freed from decarburisation and specially polished.



(1) 0·86 PER CENT C., HARD DRAWN

(2) ARMCO IRON DRAWN ONE PASS

Fig. 58

Heating to temperatures below 400° C. influences the fatigue limit of cold-drawn wire. In general the fatigue limit is increased by this tempering, but occasionally it is decreased.

Values of ±44 tons per square inch have been obtained on wire containing 0·85 per cent. carbon, and it seems probable that when all the factors influencing the fatigue limit of wire have been fully investigated values of the order of ±50 tons per square inch will be obtained. At present the fatigue limit of the ordinary wire of commerce is only about half this value.

Endurance.—Some years ago the author suggested that the endurance or life of a wire under stresses in excess of the limiting fatigue stress was possibly more important from some points of view than the actual fatigue limit. This question is discussed later in Chapter VIII. with reference to rope wire, but some indication may be given here as to how this property of endurance is influenced by the factors which govern the fatigue limit. This point has been investigated to some extent by Gill and Goodacre, but their results did not carry the matter to a conclusion. They do, however, show sufficient evidence of difference between this property of endurance and the limiting fatigue stress itself to make fuller research on this matter of considerable importance.

The matter may be made clear at the outset by a comparison of the curves in Fig. 58, which illustrate extreme conditions. Curve 2 is the endurance curve of armco iron drawn 1 pass. Curve 1 is that of a hard-drawn high carbon steel wire. Curve 2 has not become asymptotic even at twelve million stress cycles, while curve 1 reaches that condition at about 600,000.

Surely the extreme difference in properties represented by these two curves is not without significance. Gill and Goodacre have attempted to express this quantitatively by plotting the endurance limits for 125,000, 250,000, and 500,000 stress cycles obtained on the various wires they tested along with the limiting fatigue stresses. One important point indicated by their results is that wire with a decarburised skin will endure stresses causing failure after 125,000 reversals almost as well as wire in which the decarburised envelope has been removed, and it is suggested that at higher stresses, such as might cause failure at 50,000 cycles, the decarburised wire may even be superior. Further support for this idea is to be found in the fact that bends and torsions are almost invariably higher in decarburised wire.

If, then, greater endurance under high stresses for limited periods has any importance it may prove that decarburisation is in some cases beneficial and that for many purposes the removal of the decarburised skin would not improve the wire and might even prove harmful.

DENSITY

Many conflicting results have been obtained by those who have investigated the influence of cold working on the specific gravity of metals. The natural supposition is that cold working will increase the density of metals, and some of the earlier investigators found this. More recently, however, the most careful determinations have shown that the density is distinctly decreased by cold work. The reason for these discrepancies, apart from the obvious one of the difficulty in making accurate determinations, is that both statements are correct. There is undoubtedly in many metals a permanent increase in density due to working either hot or cold, since cast metal is almost inevitably somewhat porous. Small cavities or blowholes tend to be closed up during forging or rolling, and the density of the metal is slightly increased. Cold-working operations undoubtedly carry on to some extent the good

work of hot working, and one of the effects may be a slight increase in density. In order to illustrate this the following determinations made on medium steel bar ¾ inch diameter may be given:

(1) As rolled and patented	Density	7·830
(2) Hard drawn to 0·450 inch diameter . . .	,,	7·8242
(3) 0·450 inch diameter bar repatented . . .	,,	7·8488
(4) Hard drawn to No. 6 S.W.G. (0·192 inch) . .	,,	7·8197
(5) No. 6-gauge wire annealed	,,	7·836

Goerens [8] encountered this double effect on the density, and, in order to eliminate it, made his determinations on the same specimens first as cold worked and second as annealed. He states, however, that annealing has an influence of its own apart from the mere removal of the effects of cold working. Annealing in itself has, of course, a profound influence on the physical properties, depending entirely on the conditions of temperature, time, and rate of cooling, etc., but the effect of any variation of these on the density is certainly negligible in comparison with those of the permanent effects of cold working and the removal of the temporary effects. The following results of determinations, made by the author on two separate bars of hard drawn armco iron, before and after annealing at 540° C., are quite in accord with Goerens' results.

Armco Iron ¾ inch Diameter Normalised at 900° C. and drawn without Annealing to 0·437 inch Diameter

Density	
Hard drawn	*Annealed at 540° C.*
7·8552	7·8675

That there is also a fairly though not quite constant decrease in density due to increasing amounts of deformation at the normal temperature is evident from the following determinations made by O'Neill [9] on pure iron deformed by direct tensile stress.

Reduction in Area per cent. by Direct Tensile Stress	*Density*
0	7·858
2·4	7·8586
10·0	7·8558
16·9	7·8452
17·8	7·8464
19·5	7·8443
24·2	7·8393
47·5	7·7927

Similar results have been obtained in other metals with the exception of bismuth.

The following values obtained by Kahlbaum [10] on platinum may be given by way of illustration:

Rolled and forged rod 3 millimetres diameter . .	21·4314
Cold-drawn wire 1 millimetre diameter . . .	21·4136
Same wire annealed 3 minutes at white heat . .	21·4314
Cold drawn to 0·7 millimetres diameter . . .	21·4181
Same wire annealed 3 minutes at white heat . .	21·4314
Cold drawn to 0·4 millimetres diameter . . .	21·4142
Same wire annealed 3 minutes at white heat . .	21·4308

Without going deeper into the matter here, then, it may be taken as now definitely established that plastic deformation decreases the density of metals and that the slight permanent increase occasionally found is due to more or less accidental causes.

ELECTRICAL AND MAGNETIC PROPERTIES

It is to be expected that cold work which alters the mechanical properties of metals to such a marked degree should also affect the electrical conductivity and

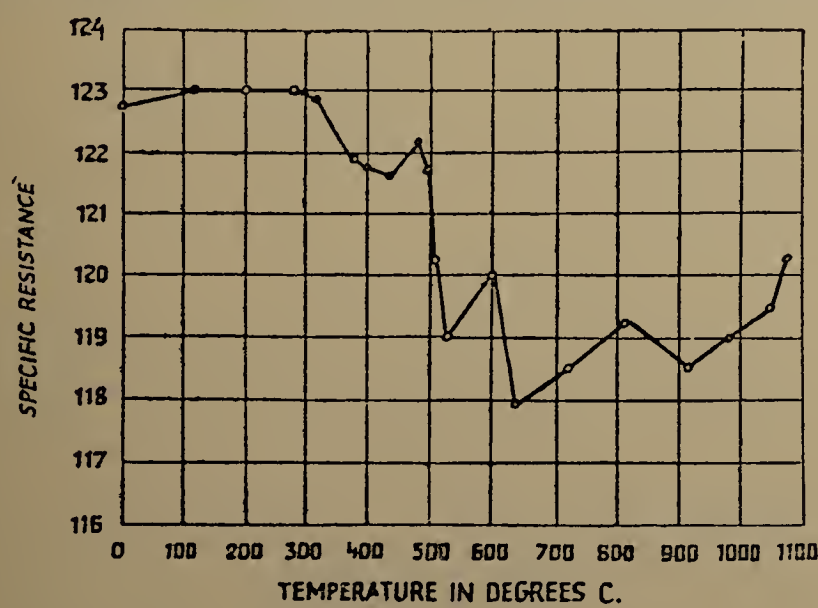


Fig. 59. (Goerens.)

particularly the magnetic properties. It is generally held that the conductivity of any particular metal is greatest in the annealed condition, but some have found the reverse and obtained a decrease in resistance due to cold work. Goerens [8] found only a very slight increase, amounting to 2·3 per cent. in resistance, and stated that, "It was only after comparing the results of measurements on the various specimens before and after annealing that a diminished conductivity was observed to result from cold working." The effect was more distinct in the mild steels, and it is of interest to note that a distinct drop in the specific resistance of these was observed when the specimens were annealed at 520° C., as may be seen from Fig. 59, repro-

duced from Goerens' report; a result which clearly proves the effects are due to cold working, since that is the temperature at which thermal equilibrium in iron is reached and recrystallisation sets in. It must be remembered, however, as Goerens points out, that annealing has an influence of its own, particularly on those physical properties other than mechanical, or, as the author prefers to put it, some of the effects of cold working are permanent.

MAGNETIC PROPERTIES

Various records of a more or less isolated and incoherent nature exist illustrating the effect of strain on the magnetic properties of iron, but the only work, so far as the author is aware, which is at all comprehensive, is that of Goerens. His investigation into the effect of cold working on the magnetic properties of iron and steel forms probably the most valuable portion of his admirable report on the effects of cold working in general. It is of particular importance here, since the form of cold work employed in his research is wire-drawing and not, as in most of the earlier work on the subject, direct straining.

The following values for the magnetic properties of wire 1·58 millimetres thick, before and after straining, are given by Ewing in his work, *Magnetic Induction in Iron and Allied Metals*:

	Annealed	*Strained* 10 *per cent.*
Maximum permeability	3080	670
Remanence	930	400
Coercive force	1·7	4·5
Induction, at H = 40	1230	1100

and from these it is evident that the magnetic properties are seriously altered by even slight deformation. Without attempting to go deeply into the subject here it may be stated briefly that Goerens' work fully confirmed the above results. "The maximum permeability," says Goerens, "falls from 1091 in the hot-rolled wire to 380 in the end-product, with a diameter of 1 millimetre"—*i.e.* 96·5 per cent. reduction.

"Furthermore, it is noteworthy that the greatest change in the permeability takes place as early as the first drawing, that the magnetic deterioration of the material likewise is at its greatest magnitude at quite an early stage in cold working. This is thoroughly in accord with the experiments carried out by Ewing, in which the deformation was very small, although obtained in a different way from that in the present researches."

Goerens also found that the maximum permeability is not only greatly reduced by cold working, but that it occurs at a much higher field-strength. For example, in one case the maximum permeability in the hot-rolled wire is attained at a field-strength of 5·5 units, but the necessary field-strength grows to 22·5 in the case of the hard-drawn final product. "This demonstrates that, even if important alterations of the material are engendered during the first drawings, yet further additional

drawings act in such a way as to render necessary higher field-strengths in order to reach the best value for the permeability."

Some of the more important of Goerens' results are given in Tables 18 to 23.

TABLE 18 (GOERENS)

Basic Bessemer Steel, 0·07 per cent. Carbon. Magnetic Properties when Magnetised up to Point of Saturation

Mechanical Treatment	*Reduction per cent.*	*Maximum Field-Strength H-max.*	*Maximum Induction B-max.*	*Maximum Permeability μ*	*H at μ-max.*	*Remanence*	*Coercive Force*	*Hysteresis E erg. per cm.³*
Hot rolled (untreated)	..	178·0	18,400	1,091	5·5	8,200	3·5	24,400
Subjected to 1 drawing.	41·6	180·0	18,200	442	10·4	6,600	7·0	43,950
Subjected to 4 drawings	85·7	178·9	18,300	420	19·4	8,000	12·7	75,200
Subjected to 6 drawings	93·2	178·8	18,250	400	21·9	9,200	13·0	77,200
Subjected to 8 drawings	96·5	178·0	18,200	380	22·5	9,800	14·8	78,650

TABLE 19 (GOERENS)

Basic Bessemer Steel, 0·07 per cent. Carbon. Magnetic Properties when Magnetised (a) *at Constant Field, H = 100*; (b) *up to Constant Induction, B = 15,000*

Mechanical Treatment	*Reduction per cent.*	*Magnetic Field = 100*		*Induction B = 15,000*	
		Induction B	*Hysteresis E*	*Field-Strength H*	*Hysteresis E*
Hot rolled (untreated) .	..	17,200	22,360	31·6	15,550
Subjected to 1 drawing .	41·6	16,700	37,600	68·0	30,900
,, ,, 2 drawings .	70·5	16,900	48,400	62·0	51,600
,, ,, 3 ,, .	79·5	17,000	50,200	57·6	49,700
,, ,, 4 ,, .	85·7	16,750	49,100	65·7	54,600
,, ,, 5 ,, .	89·2	16,850	60,000	60·9	57,900
,, ,, 6 ,, .	93·2	16,600	54,700	64·7	58,000
,, ,, 7 ,, .	95·2	16,650	63,900	60·2	56,900
,, ,, 8 ,, .	96·5	16,500	67,000	58·4	59,700

TABLE 20 (GOERENS)

Open-Hearth Steel, 0·55 per cent. Carbon. Magnetic Properties when Magnetised up to Point of Saturation

Mechanical Treatment	*Reduction per cent.*	*Maximum Field-Strength H-max.*	*Maximum Induction B-max.*	*Maximum Permeability μ*	*H at μ-max.*	*Remanence*	*Coercive Force*	*Hysteresis E erg. per cm.³*
Hot rolled (untreated)	..	180·2	17,850	471	17·0	9,500	10·0	60,100
Subjected to 1 drawing.	34·0	180·2	17,550	306	28·7	7,200	18·0	89,700
Subjected to 3 drawings	62·6	180·7	17,400	320	32·0	9,600	17·4	93,400
Subjected to 4 drawings	78·6	180·9	17,550	312	31·0	8,700	18·5	98,200
Subjected to 5 drawings	86·5	181·0	17,350	297	31·6	11,600	18·5	104,000

TABLE 21 (GOERENS)

Open-Hearth Steel, 0·55 per cent. Carbon. Magnetic Properties when Magnetised (a) *at Constant Field, H = 100*; (b) *up to Constant Induction, B = 15,000*

Mechanical Treatment	*Reduction per cent.*	*Magnetic Field = 100*		*Induction B = 15,000*	
		Induction B	*Hysteresis E*	*Field-Strength H*	*Hysteresis E*
Hot rolled (untreated) .	..	16,000	49,400	68·4	43,950
Subjected to 1 drawing .	34·0	17,000	83,000	73·2	67,800
,, ,, 2 drawings .	55·0	16,600	82,200	70·9	75,000
,, ,, 3 ,, .	62·6	16,600	91,300	71·8	74,370
,, ,, 4 ,, .	78·6	16,850	89,900	72·7	77,400
,, ,, 5 ,, .	86·5	15,900	91,000	73·0	78,400

TABLE 22 (GOERENS)

Open-Hearth Steel, 0·78 per cent. Carbon. Magnetic Properties when Magnetised up to Point of Saturation

Mechanical Treatment	*Reduction per cent.*	*Maximum Field-Strength H-max.*	*Maximum Induction B-max.*	*Maximum Permeability μ*	*H at μ-max.*	*Remanence*	*Coercive Force*	*Hysteresis E erg. per cm.³*
Hot rolled (untreated)	..	179·2	16,600	327	27·5	10,200	15·0	80,600
Subjected to 1 drawing.	25·4	179·0	16,700	290	38·4	8,600	19·6	118,700
Subjected to 2 drawings	36·7	179·0	16,850	284	38·7	9,100	18·5	112,400
Subjected to 3 drawings	47·5	179·3	17,000	279	38·3	10,200	22·7	125,900
Subjected to 4 drawings	58·5	179·0	16,700	282	39·2	9,900	22·1	129,000
Subjected to 5 drawings	67·5	179·0	20,100	281	39·3	11,800	22·0	129,500

TABLE 23 (GOERENS)

Magnetic Properties when Magnetised (a) *at Constant Field,* $H = 100$; (b) *up to Constant Induction,* $B = 15{,}000$

Mechanical Treatment	*Reduction per cent.*	*Magnetic Field = 100*		*Induction B = 15,000*	
		Induction B	*Hysteresis E*	*Field-Strength H*	*Hysteresis E*
Hot rolled (untreated) .	..	15,300	71,100	89·2	68,150
Subjected to 1 drawing .	25·4	14,950	90,700	91·3	79,700
,, ,, 2 drawings .	36·7	16,300	98,300	79·7	80,300
,, ,, 3 ,, .	47·5	17,000	97,900	73·4	81,000
,, ,, 4 ,, .	58·5	14,700	106,000	80·0	82,000
,, ,, 5 ,, .	67·5	18,000	106,400	60·0	79,200

Another point of interest in connection with the magnetic properties is the permanent effect of cold working. In one instance—viz. that of silicon iron—it has been found that the refinement of grain due to wire-drawing has resulted in a permanent decrease in permeability, while in other cases this effect is unnoticed. This may be due to the fact that silicon iron owes its high permeability to its exceptionally large grain, while other high permeability alloys do not.

RESISTANCE TO CORROSION AND SOLUBILITY IN ACID

It is now generally known that cold working increases the solution potential and the solubility of metals in acid. Cases are found also in wire ropes where corrosion has occurred with unusual rapidity. The whole question of corrosion is so extremely complicated that no very definite conclusions can be drawn at present as to what causes excessive corrosion in particular instances. Still less is it possible to manufacture wire on a commercial scale in such a way that its resistance to corrosion will be readily controlled. As already mentioned in Chapter II., Stead and Wigham found that copper in steel wire had a beneficial effect on the solubility in acids, but it does not follow that such wire will, under service conditions, resist atmospheric corrosion more readily.

Goerens found that the solution potential is increased by cold drawing and reduced by reheating the cold-drawn wire to increasing temperature. Some figures showing the solubility in sulphuric acid are also reproduced from his paper and may be compared with some of the author's own results. One point of great practical importance, found by Goerens and also by the author, is that the action of the acid on the drawn wires does not commence so rapidly as on the hot rolled or annealed rod. This fact, which the author attributes to the smooth skin of the drawn wire, has a considerable bearing on the resistance to atmospheric corrosion in service and may, in some cases, where the conditions are not too severe, be sufficient to counteract the greater solubility due to cold working. It has been suggested that determinations of solubility in acid might be used to indicate the amount of cold work a wire has received. The results, however, are at best extremely uncertain, and a much safer guide is to be found in an examination of the microstructure. The differences in solubility, due to causes other than cold work, are so great that, unless Goerens' method of testing the same wire before and after annealing be adopted, this method of estimating the amount of reduction by cold work cannot be employed.

Some typical results obtained by Goerens are shown in Tables 24 to 26.

[TABLE 24

TABLE 24 (GOERENS)

Basic Bessemer Steel, 0·07 per cent. Carbon. Rate of Solution in Sulphuric Acid

Mechanical Treatment	*Reduction per cent.*	*Quantity in Milligrammes per mm.² of Surface dissolved in Deci-normal Sulphuric Acid at end of*					
		Untreated			*Annealed*		
		1 *hour*	4 *hours*	16 *hours*	1 *hour*	4 *hours*	16 *hours*
Hot rolled (untreated) .	..	0·44	1·29	5·09	0·24	0·32	1·24
Subjected to 1 drawing .	41·6	0·46	1·46	6·66	0·26	0·39	2·78
,, ,, 2 drawings	70·5	0·12	1·47	9·97	0·27	0·42	2·85
,, ,, 2 ,,	79·5	0·07	2·57	25·07	0·20	0·30	2·71
,, ,, 4 ,,	85·7	0·20	2·80	26·80	0·25	0·40	2·74
,, ,, 5 ,,	89·2	0·17	2·67	30·67	0·30	0·41	2·09
,, ,, 6 ,,	93·2	0·16	2·32	26·72	0·22	0·37	2·13
,, ,, 7 ,,	95·2	0·35	2·58	..	0·23	0·40	2·01
,, ,, 8 ,,	96·5	0·20	3·75	..	0·22	0·35	1·77

TABLE 25 (GOERENS)

Open-Hearth Steel, 0·55 per cent. Carbon. Rate of Solution in Sulphuric Acid

Mechanical Treatment	*Reduction per cent.*	*Quantity in Milligrammes per mm.² of Surface dissolved in Deci-normal Sulphuric Acid at end of*					
		Untreated			*Annealed*		
		1 *hour*	4 *hours*	16 *hours*	1 *hour*	4 *hours*	16 *hours*
Hot rolled (untreated) .	..	0·15	0·38	1·30	0·16	0·43	1·13
Subjected to 1 drawing .	34·0	0·15	0·74	3·94	0·18	0·32	1·06
,, ,, 2 drawings	55·0	0·12	0·78	4·78	0·22	0·57	1·47
,, ,, 3 ,,	62·6	0·06	1·08	6·23	0·26	0·59	1·79
,, ,, 4 ,,	78·6	0·11	1·27	6·27	0·24	0·47	1·15
,, ,, 5 ,,	86·5	0·11	1·55	7·35	0·22	0·40	0·78

TABLE 26 (GOERENS)

Open-Hearth Steel, 0·78 per cent. Carbon. Rate of Solution in Sulphuric Acid

Mechanical Treatment	*Reduction per cent.*	*Quantity in Milligrammes per mm.² of Surface dissolved in Deci-normal Sulphuric Acid at end of*					
		Untreated			*Annealed*		
		1 hour	*4 hours*	*16 hours*	*1 hour*	*4 hours*	*16 hours*
Hot rolled (untreated) .	..	0·09	0·26	0·51	0·11	0·20	0·45
Subjected to 1 drawing .	25·4	0·07	0·24	0·64	0·10	0·15	0·37
,, ,, 2 drawings	36·7	0·06	0·29	1·41	0·12	0·21	0·48
,, ,, 3 ,,	47·5	0·04	0·20	1·17	0·10	0·20	0·54
,, ,, 4 ,,	58·5	0·05	0·37	1·85	0·12	0·22	0·48
,, ,, 5 ,,	67·5	0·09	0·55	1·96	0·10	0·16	0·46

TABLE 27

Armco Iron—Solubility in 1 per cent. Sulphuric Acid

Size	*Condition*	*Loss in mg. per square cm.*			
		24 hours	*48 hours*	*72 hours*	*120 hours*
0·210 in.	As rolled	1·75	2·45	3·39	6·1
0·210 ,,	Annealed	1·53	2·53	3·38	6·8
0·190 ,,	Drawn 1 pass	1·7	2·55	3·33	6·85
0·175 ,,	,, 2 passes	1·97	2·75	3·9	6·95
0·158 ,,	,, 3 ,,	1·98	2·71	4·03	7·6
0·140 ,,	,, 4 ,,	1·57	2·69	4·90	10·22
0·125 ,,	,, 5 ,,	1·35	2·61	4·58	10·27
0·190 ,,	Blued at 400° C.	1·05	1·93	..	5·6
0·175 ,,	,, ,,	0·90	1·95	..	5·9
0·158 ,,	,, ,,	1·06	2·33	..	5·92
0·140 ,,	,, ,,	1·88	2·53	..	5·99
0·125 ,,	,, ,,	1·89	2·52	..	6·15

The results on armco iron are particularly interesting, because they show the effect of cold work on a metal said to offer more resistance to corrosion than most mild steels. The effect of cold work is, therefore, more clearly shown, because of the absence of other interfering factors.

The following points appear to be established by this experiment:

(1) Cold working increases the solubility in sulphuric acid considerably, and the extent to which it does so depends largely on the amount of reduction. After a reduction in area by drawing of 67 per cent. the solubility in 120 hours' continuous immersion is increased 67 per cent.

(2) The effect of blueing in this material is to remove completely the increase in solubility due to drawing, the sample drawn 5 passes and blued having the same solubility as the normalised sample.

(3) Although the drawn wire is more soluble than the normalised rod after a sufficiently long period of immersion, it is not so quickly attacked. This is obviously a very important point, and it is due in all probability to the increased resistance of the smoother surface obtained by drawing.

TABLE 28

Solubility of Patented Steel Wire in 1 per cent. Sulphuric Acid

Chemical Analysis—	Carbon	0·50 per cent.
	Silicon	0·11 ,,
	Manganese	0·48 ,,
	Sulphur	0·033 ,,
	Phosphorus	0·014 ,,

Size	*Condition*	*Loss in mg. per square cm. 120 hours*
0·210 in.	As rolled	26
0·182 ,,	Patented	58
0·162 ,,	Drawn 1 pass	157
0·157 ,,	,, 2 passes	212
0·133 ,,	,, 3 ,,	233
0·114 ,,	,, 4 ,,	273
0·097 ,,	,, 5 ,,	283
0·080 ,,	,, 6 ,,	321

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CHAPTER VII

THE EFFECT OF HEAT-TREATMENT AFTER COLD WORK

The cold-worked condition of metals is totally different from the normal, and it is to be expected that the effect of heat on it will also be different. Nor is it so easy to remove the effects of cold work by heat-treatment, as is often supposed. Complete removal of these is probably impossible. Although the general hardening due to cold work is removed by annealing at the temperature of recrystallisation or "thermal equilibrium," there are certain permanent effects which may be beneficial or otherwise according to circumstances. Obviously the microstructure is changed, since the grain size must necessarily be, to some extent, proportional to the dimensions of the metal section, and we cannot ordinarily expect the same size of grain in a 30-gauge wire as in a 5-gauge rod, although it is true that in exceptional circumstances it can be made to grow larger. In general, therefore, the grain size is reduced by cold work followed by annealing, and this in itself may affect certain properties. For example, the magnetic permeability of silicon iron is profoundly affected by the reduction in grain size due to wire-drawing.

Apart from the refining of the grain there are other permanent effects of cold work: grouped together, these may be considered, to some extent, as a continuation of the beneficial effects of hot working. This is an aspect of cold work not generally realised. In brief, many of the casting defects not entirely eliminated by hot working are finally removed by cold working; all traces of the original dendritic structure with its inherent weakness is finally lost, and the density of the metal is increased by the closing up of the pores. This increase in density is not to be confused with any change associated with general hardening of cold-worked metal; we are referring here only to the increase in density which persists after the cold-worked metal has been annealed.

Bearing these very real and permanent effects of cold work in mind, we can now go on to discuss the effect of heating to gradually increasing temperatures.

There is distinct evidence that some of the effects of cold work are not permanent even at the ordinary temperature. Mere ageing undoubtedly influences the physical properties to some extent. The changes become more pronounced, however, as the temperature increases; thus boiling in water produces distinctly measurable alterations in the elastic properties, and the limit of proportionality has been raised to over 80 per cent. of the ultimate strength in a cold-drawn wire

heated to just under 400° C. There is little doubt that the modulus of elasticity is also affected by heat-treatment after cold work. Up to 400° C. there is a distinct stiffening or hardening effect, but above this point the cold-worked metal begins to soften again. The metal under consideration here is, of course, steel. Other metals, however, appear to behave similarly, only in a different degree and under different temperature conditions.

Above 400° C. in cold worked steel there is a gradual decline in the hardening effect, but the metal is not greatly softened until a temperature varying from 520° C. in mild steel to 650° C. in high carbon steels is reached. About 520° C. the free iron or ferrite recrystallises, forms new grain boundaries, and the grains which have been distorted by cold work—in the case of wire, elongated—again become polygonal and equi-axial. The sorbitic or pearlitic areas regarded in the mass remain distorted, but when a temperature of about 600° C. is reached a distinct internal change takes place. This change in the microstructure of the pearlitic or sorbitic areas is evident, at low magnifying powers, only by a slight decrease in contrast, or a chequered effect in the dark areas. But at high powers (Fig. 28) it is seen to be due to a divorce of the constituents—the carbide or cementite has coalesced into globules surrounded by the ferrite; as the temperature is increased this divorce becomes more pronounced, and, although the change takes place fairly rapidly, time has the effect of making it more complete. Thus steel is brought into its softest condition by cold working, followed by soaking for an hour or two just below the critical range of temperature.

Heating above the critical range, for the most part, obliterates the effects of the cold work—with the exception of the permanent effects previously mentioned. If the heating has been gradual, however, and time has been allowed for the formation of large globules of cementite before the transformation points are reached, these large globules may persist even in hypo-eutectoid steels at a temperature as high as 900° C. Thus it is possible to have globules of free cementite existing in a hypo-eutectoid steel, as is shown in Fig. 33. To remove these it is necessary, if the heating be fairly rapid, to reach a temperature of about 950° C., or even higher, when the cementite is redissolved in the γ (gamma) iron.

The effect of heat-treatment after cold work has an important bearing from the practical point of view in such operations as hot galvanising and tinning. It is also of importance in relation to the physical properties, particularly those related to the elasticity, and any investigation of the underlying theories of plastic flow demands a careful study of the gradual removal of the effects by ageing and heat-treatment.

Although aware that slight modification of the physical properties of cold-worked metals, due to ageing and boiling, had been observed by some investigators, the author did not find any evidence of it in wire until engaged in an investigation on the heat-treatment of "streamline" wires for aircraft. On checking some reverse bend tests on these wires after a lapse of about four months he found a distinct decrease in the number of bends the wire would stand. The extent of this decrease

was about 25 per cent., and at the time it was considered due possibly to some cause other than mere ageing, such as slight corrosion, especially as ordinary round wire had never been found to alter like this, even after lying for very much longer periods. These results, however, have since been definitely confirmed, as shown in Table 29. It has been found that this effect of ageing and boiling is distinct only in material which has been rolled and not drawn; and the probable explanation is that, in ordinary drawing, the wire is heated by friction to a temperature sufficiently high to leave it in a condition similar to that produced by ageing and boiling. But in rolling it there is not so great an increase in temperature. This explanation appears all the more reasonable in view of the fact that "wet-drawn" wire is generally found to be tougher than "dry-drawn" wire, and that the latter can be made as tough by using water-cooled dies or blocks.

TABLE 29

Treatment	*No. of Bends*	
	¼-in. Wire bent round Radius of 0·48 in.	*½-in. Wire bent round Radius of 0·55 in.*
As rolled	28·5	11·0
Then aged 6 months . .	27·5	6·5
,, heated to 100° C. . .	26·5	10·0
,, aged 6 months . .	25·0	6·0
,, heated to 350° C. . .	22·5	3·0
,, aged 6 months . .	21·0	1·0

The almost mobile condition of freshly cold-worked metal is not only a matter of academic interest, but is of some importance in relation to continuous drawing and ordinary testing. It is indeed possible to improve the apparent ductility of a wire, without decreasing its tensile strength, by working it slightly backwards and forwards, or by passing it through a system of pulleys, over and under alternately, and the rapid removal by water-cooling of the heat generated in drawing has an effect which is far from negligible.

Heating to temperatures below 400° C. instead of removing the effects of cold work actually intensifies them. The slight hardening or stiffening effect, due to ageing and boiling, becomes much more pronounced at temperatures between 200° and 400° C. in steel; up to 200° C. the tenacity and elastic limit are increased. These temperatures will no doubt vary slightly according to the composition of the steel and the amount of cold work it has received, but they represent average conditions. The effect of heating—or "blueing," as it is often called—at these comparatively low

temperatures is more pronounced in cold-rolled material, and in drawn material such as thick bars, shapes, and tubes, where the speed of drawing is sufficiently slow to prevent any great heating due to friction. In round wire drawn on a block, where the speed is greater and no water-cooling system is adopted, a certain amount of heating immediately takes place; and not only is the effect of subsequent ageing or boiling practically nil, but even "blueing" has less effect. For example, the operation of tinning at a temperature of 250° to 300° C. has less effect on a hard-drawn wire than on a cold-rolled article. That "blueing" has a pronounced effect on cold-worked material is now widely appreciated. Springs made from hard-drawn wire are now frequently "blued."

The value, or otherwise, of such heat-treatment after cold work depends entirely on the purpose for which the wire is required. The question here is that of the requisite balance between elastic properties and ductility. Although the elastic limit and, to a slight extent, the modulus are raised by this treatment, the steel undoubtedly loses ductility after it, and sometimes becomes brittle.

The mobility of cold-worked material is, in many instances, a safeguard against sudden failure; it gives a security analogous to that which the structural engineer looks for in the definite yield point and high elongation of mild steels.

Several factors have to be considered, then, in making a decision regarding the advantages or disadvantages of mild blueing after cold work. In this connection it may be of interest to quote from the report on "The Materials of Construction used in Aircraft and Aircraft Engines," by Lieut.-Col. C. F. Jenkin, and to reproduce some of the results contained therein. Referring to the heat-treatment of streamline wires this report states:

"The blueing of cold-worked metal is for many purposes very advantageous and has been strongly advocated for streamline wires. Considerable numbers of streamline wires in service have been so treated, and many tests have been undertaken to prove their superiority over untreated wires, but none of these tests have shown that heat-treatment is beneficial. The question cannot, however, be finally settled till a completely satisfactory method of testing is devised. The latest specification forbids heat-treatment unless special permission is granted to use it.

"A number of investigations have been made to determine the effect of heat-treatment on the properties of the wires as shown by the ordinary mechanical tests."

The results of a large number of tests made by Professors Edwards and Goodman are then given, and the report goes on to state:

" The curves show the well-known effects of heat-treatment on cold-worked steel. The elastic limit (limit of proportionality) is considerably raised by blueing at temperatures between 350° and 500° C. The ultimate strength is not much affected till temperatures of 400° or 500° C. are reached, and then begins to fall off rapidly, at which temperature the elongation begins to increase.

"The effect of heat-treatment on the number of reverse bends the wire will stand is shown in the following test made in Sheffield, and somewhat similar results were obtained at Bruntons' Research Laboratory:

"Reverse Bend Test on $\frac{5}{16}$-in. Streamline Wire

Cold rolled . . .	13	reverse bends	before fracture
Blued at 350° C. . .	12	,,	,,
,, 400° C. . .	8	,,	,,
,, 450° C. . .	8	,,	,,
,, 500° C. . .	10	,,	,,
,, 550° C. . .	12	,,	,,

"The raising of the elastic limit produced by blueing at temperatures about 400° C. might at first sight appear to be an advantage, but the elastic limit has really very little meaning and is quite unimportant for wires used in tension. The effect of the blueing is merely to release the internal stresses in the wire, and there is no reason to suppose that these stresses do any harm. There is, on the contrary, much evidence to show that cold-worked steel is a reliable material; it is used for the wires in all wire ropes, for bicycle and motor-car wheel spokes, and for many other purposes."

Since these tests were made the author has carried out confirmatory tests, which have already been reproduced (Fig. 54). The point of particular interest which the check tests confirmed was the effect of ageing, not only before heating but even after heating—a more surprising result, which suggests that cold-worked material tends continually to revert to the stable condition.

The effect of blueing cold-worked metal has recently been studied by several investigators. It has been definitely found beneficial for structural members made from cold-drawn tubes and cold-rolled strip where failure occurs through exceeding the elastic limit in compression. In this connection also some interesting results will be found fully reported in the above-mentioned report on "The Materials of Construction used in Aircraft and Aircraft Engines."

The effect of blueing on the elastic limit in tension has already been mentioned in Chapter VI., and it has also been shown that carefully controlled alternating stresses have a similar effect on the elastic limit. It may therefore be taken as now established that the effect of blueing is due, in part at least, to the release of internal stresses. There is, however, still some difficulty in explaining all the effects of blueing in this way, and until the entire mechanism of plastic flow at normal temperatures is fully understood there will be some difference of opinion on this point. Since we are dealing in this chapter with effect rather than cause, the influence of blueing on the other properties must be considered.

Closely related to the elastic properties is the question of endurance under repeated stress reversals. Some figures have already been given in the last chapter showing how the fatigue range is slightly increased by blueing and how the cold-worked metal is more or less stabilised by this form of heat-treatment. Experience has shown, moreover, that springs made from hard-drawn wire are undoubtedly improved by blueing. The author once had occasion to put this point to the following very practical test. Some springs made from cold-rolled wire were continually

failing after a short life averaging three months, and the conditions of fracture indicated that failure was due to fatigue. A dozen of these springs were therefore blued and painted to distinguish them, with the result that a request came from the user that all springs should in future be supplied in the same condition as the painted ones. All these springs have since been supplied in the blued condition, and the trouble has in this way been completely removed.

It does not follow, however, from these results that all cold-worked material should be blued, even when subjected to repeated stress reversals. In the case of a spring it is advisable to use material with a definite maximum fatigue limit, and to

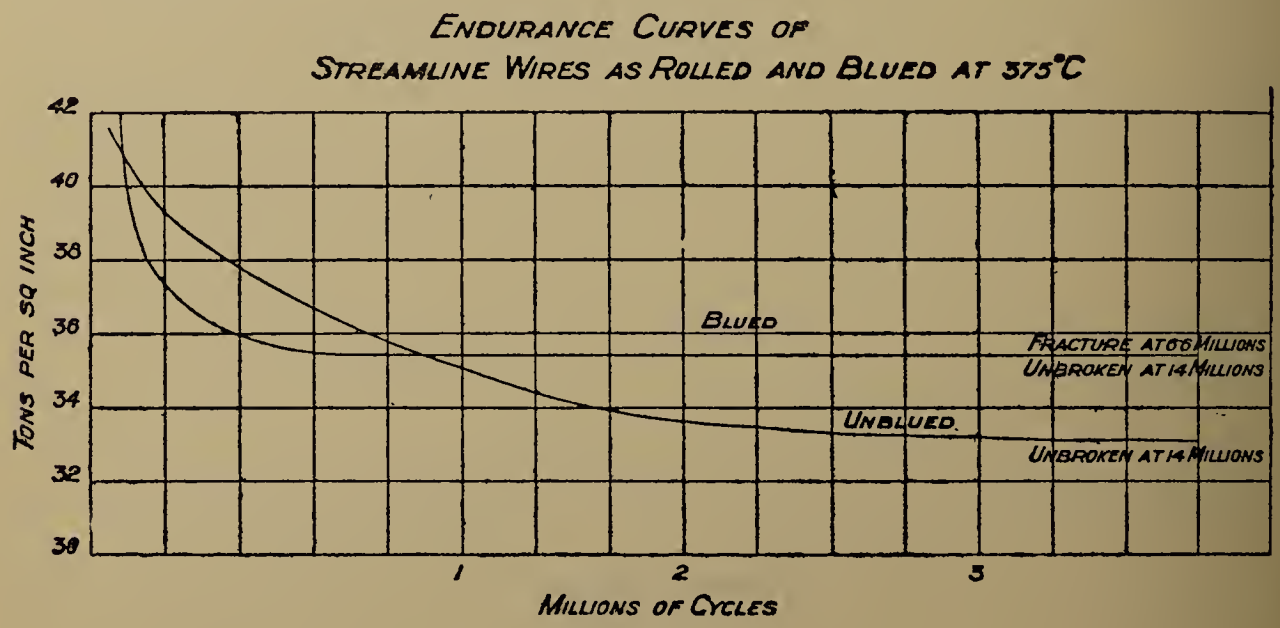

Fig. 60

know that if the material is stressed below this point it will last indefinitely, or if stressed above it it will fail rapidly. But there are many cases in service where a wire is almost inevitably overloaded at intervals. Take, for example, the case of a streamline wire, in which the following causes of failure are given by Professor Jenkin in the above-mentioned report:

1. Excessive vibration.
2. "Flapping" of loose wires.
3. Misuse of lock nuts.
4. Imperfect tuning of duplicate wires.
5. Overloads due to landing shocks.
6. Overloading in stunt flying.
7. Defects in wires.

Thus it is evident that the safe load is occasionally surpassed whether the wire is blued or not. This overloading may alter the original fatigue limit of the material considerably; and although the wire may not actually fail during the "stunt," or whatever caused the overload, but at some later period during ordinary flight, or

even when the machine is merely gliding, yet it seems highly probable that the real cause of failure is the momentary overload.

Fatigue failures in such wires would therefore seem to be due rather to serious but intermittent overloads, followed by sudden alterations in vibration—it is well known that the sudden arrest of vibration is a frequent source of fatigue failures—and there is a distinct element of uncertainty here regarding the stress conditions.

Now there is one very important difference between the endurance curves of a blued and unblued wire, as will be seen from Fig. 60—viz. that the rate of breakdown

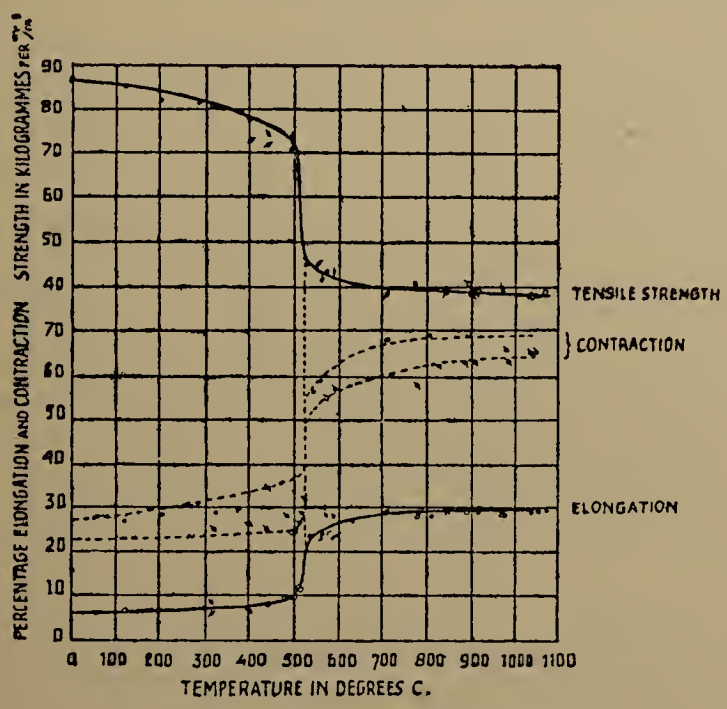

Fig. 61. (Goerens.)

is very much more rapid in the blued condition once the fatigue range is passed. This simply means that the unblued wire is much more ductile under alternating as well as under ordinary stresses—a fact which is fully confirmed by reverse bend and Izod tests. There is a tendency nowadays to regard ductility as of less importance, and the view is often expressed that the rate of breakdown is of no importance once the fatigue range has been exceeded. Theoretically, no doubt, this is sound, but who can guarantee that in practice the stresses on a structural member will always be within the safe range? Until the designer has a complete knowledge of all the stresses to which his structure will be subjected, and can guarantee that occasional overloading is impossible, is it not wiser to have the additional safeguard of ductility in the metal in order to minimise the risk of sudden failure? Take the case of wire ropes. It is probably impossible in many cases to guarantee absolute freedom from fatigue, and, since the life of the rope is limited in other ways, the question of the amount of work the wire will stand before failure becomes important. One of the chief causes of distrust of cold-worked material is indeed the alleged lack of ductility, and it seems to the author extremely unwise to increase the distrust by blueing wires

and so making them more brittle for the sake of a very small increase in the fatigue limit.

Turning now to the effect of heating to higher temperatures, we find that above 400° C. the hardening or stiffening effect begins to decline; but not until a certain definite temperature is reached, ranging from 520° C. in mild steel to about 580° C. in high carbon steel, does any great softening effect occur. At 520° C. in mild steels there is a sudden softening due to complete recrystallisation of the ferrite, but as the carbon content of the steel is increased the softening is more gradual.

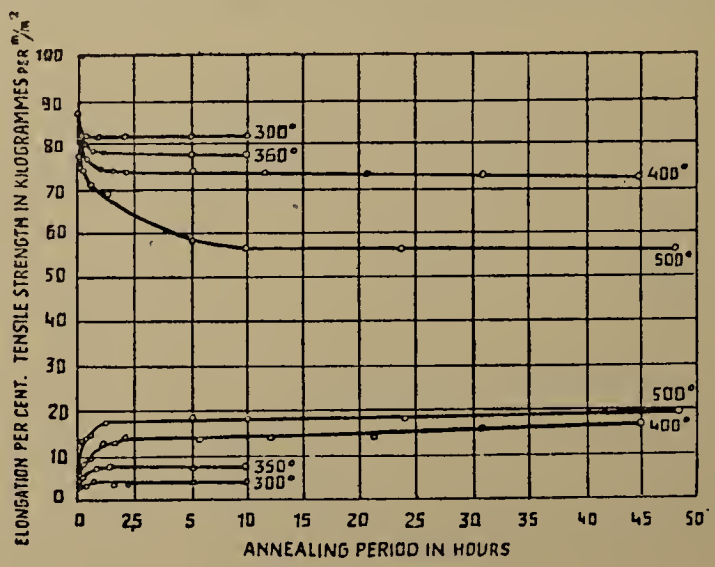

Fig. 62. (Goerens.)

The annealing of cold-worked mild steel has been studied by Goerens, Chappell, and others, while the author has devoted more attention to the medium steels. Some of the more important results of these investigations are detailed below.

In Fig. 61, reproduced from Goerens' report, the effect of heating a low carbon basic Bessemer steel wire is shown. This had been reduced to 2·7 millimetres from rolled rod 7 millimetres thick in 5 passes—*i.e.* 85 per cent. reduction in diameter. Its chemical composition was as follows:

Carbon	*Manganese*	*Silicon*	*Sulphur*	*Phosphorus*	
0·080	0·39	0·008	0·056	0·059	per cent.

Period of heating at each temperature, twenty-five minutes.

Fig. 62 shows the influence of time in annealing the same steel at various temperatures.

"Regarding these results," says Goerens, "to get a desired condition by annealing, heating for a short time suffices to get the result characteristic for any special temperature. Prolonged annealing is of no use, as the properties of the material are only slightly more altered, whereas any damaging action would assert itself considerably more emphatically during a long period of annealing." Somewhat similar has been the author's experience, but with higher carbon steel wire drawn from the patented condition, time plays a more important part, and a comparison of the

results is interesting. In Figs. 63 and 64 are curves showing the effect of the duration of heating at various temperatures ranging from 400° to 600° C. on the tenacity and elongation of medium and high carbon steel wires. In these tests two series of wires were used, and in each series there were two sizes. The carbon content in one was approximately 0·45 per cent., and in the other 0·70 per cent. In the medium steel wires the tenacity as drawn was about 60 tons per square inch and the sizes of the wires were 0·140 and 0·185 inch diameter, and in the higher carbon wires the tenacity as drawn was about 100 tons per square inch, the sizes of the wires being 0·138 and

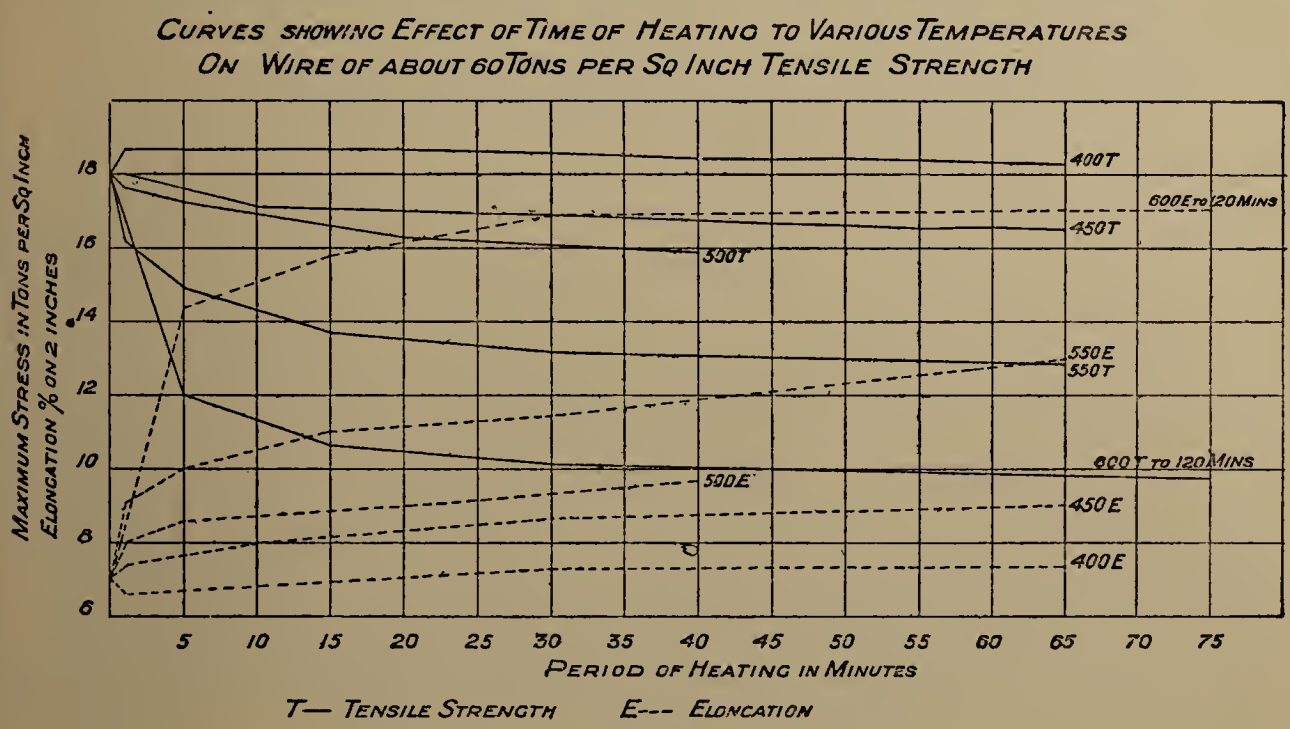

FIG. 63

0·177 inch diameter. In the present diagrams each point of the curves represents the mean result of six tests—*e.g.* in Fig. 63 each point plotted is the mean value obtained from three tests on the 0·140 inch diameter wire and three tests on the 0·185 inch diameter wire, and similarly in Fig. 64 for the higher carbon wires.

In the medium carbon steel wires (Fig. 63) there is a definite annealing effect at 550° C., but it is not nearly so distinct as Goerens' annealing temperature of 520° C. in mild steels. In the higher carbon steel wires (Fig. 64) there is scarcely any sign of a definite annealing temperature, the softening effect being incomplete even after heating for an hour at 600° C. It is therefore clear that the importance of the time-factor in any thermal treatment after cold work between 400° C. and the critical temperature becomes greater as the carbon content increases. Goerens also carried out some very interesting investigations on the same mild steel wire regarding the effect of annealing after cold work on many other physical properties, and some of his results are reproduced in Table 30.

TABLE 30 (GOERENS)

Effect of Annealing on some Physical Properties

Annealing Temperature ° C.	*No. of Bends*	*Specific Gravity*	*Magnetic Properties*		
			Maximum Permeability	*Coercive Force*	*Remanence*
As drawn	11	7·804	430	10·5	9,500
100	12·5	..	470	10·5	10,000
200	14	7·805	520	9·8	9,500
300	15	..	570	9·0	10,000
400	16	7·805	1200	7·5	12,000
500	17	7·815	1420	5·5	15,800
550	28	..	1740	4·3	..
600	29	7·820	..	..	12,700
700	30	..	1530	3·7	..
800	31	7·821	1430	..	11,500
900	31	7·822	1600	3·3	10,500

With regard to the reverse bend tests it is interesting to note that blueing at temperatures below 400° C. does not appear to make mild steel more brittle, as has been shown to be the case with the higher carbon sorbitic steel wires. The specific gravity tests are of particular interest, and in all his curves the sudden change in the physical properties at 520° C. is most pronounced.

The microscope explains clearly the results of the physical tests. In ferrite or in mild steels recrystallisation takes place immediately a definite temperature is reached—viz. the point of thermal equilibrium for iron, at which the molecules are freed from interstrain and reform into their natural crystalline arrangement. This change takes place comparatively quickly, and once it has taken place further heating has little effect. In a valuable paper by Chappell, "The Recrystallisation of Deformed Iron," the alterations in structure and the growth of the new ferrite crystals are demonstrated in great detail. When carbon is present, time is necessary to allow the cementite particles to coalesce into larger globules; and the more prolonged the annealing the greater is the divorce of the cementite and ferrite, and the softer is the steel. This explains the extreme softness of high carbon steels which have been annealed for several hours after cold work at a temperature of about 650° C.; and, from a structural point of view, it explains why annealing below the Ac_1 transformation point is generally more suitable as an intermediate heat-treatment between successive drawings for mild steels, and also for high carbon steels destined for subsequent hardening and tempering. In such a structure the soft, ductile ferrite

is most effectively freed from the restricting influence of the hard cementite, the plates of the latter having broken up and coalesced into large globules. It must be remembered, however, that this structure is not suitable for the production of high tensile wire, where the increase in grain size obtained by the patenting process is essential for hard drawing. Although the spheroidised cementite structure is desired for cold drawing wires belonging to Class I., which are only drawn 1 or, at the most, 2 passes between each annealing, such a structure is not suitable for wire belonging to Class II., and heat-treatment below the critical range cannot be substituted for patenting. This has been demonstrated by the author's actual experiments.

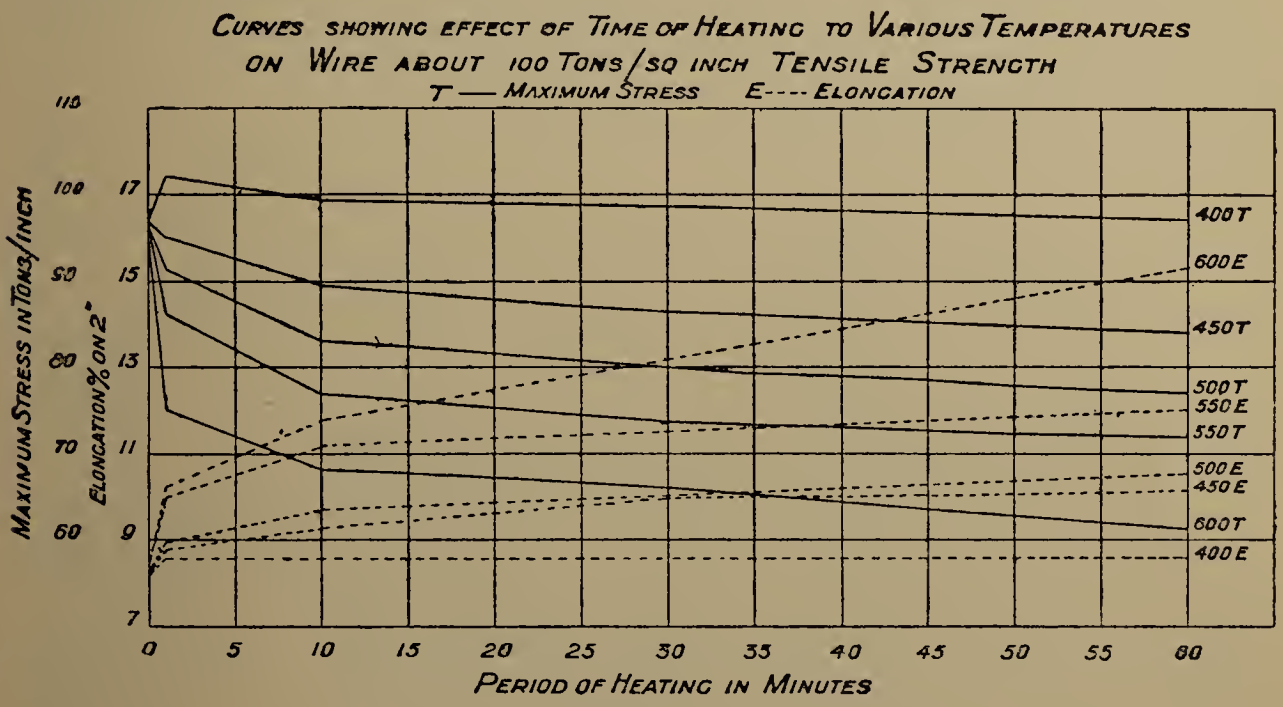

FIG. 64

The following physical tests also indicate the extreme ductility of the divorced structure produced by annealing below the Ac point after cold work:

Condition	*Yield Point Tons per sq. in.*	*Maximum Stress*	*Elongation per cent.*	*Bends through* 180°
Drawn	65·0	90	7	4
Heated to 600° C. . .	40·0	50	16	7
,, ,, 670° C. . .	27·0	40	26	12
Ac_1				
Heated to 780° C. . .	29·5	43	19	4

Heating to temperatures above the transformation point Ac_3 eliminates the effects of cold work, with the exception of those permanent effects mentioned at the beginning of the chapter; and, since such treatment brings the steel back more or less to its normal condition, it is unnecessary to pursue the matter further. The processes of tinning and hot galvanising, however, remain for consideration in this chapter.

TINNING AND GALVANISING

The operation of tinning wire is carried out for the purpose of protecting the wire from corrosion. As a protection against atmospheric corrosion, coating a steel wire with tin is of little value; in fact the steel wire is best left alone, because the presence of tin, once the surface of the steel is exposed, even by pin-holes, increases rather than decreases the trouble. This is explained by the fact that tin is electro-negative to iron, and, in the presence of corrosive media, electrolytic action is set up at the expense of the iron. The opposite effect takes place with zinc, and so long as it is present on the surface the iron is not attacked. Zinc, however, cannot be used in the presence of acid, or in an acid atmosphere, and there is still a limited demand for tinned wire.

In the operation of tinning, the wire is heated to a temperature between 250° and 300° C., which has the same effect on it as "blueing"—*i.e.* the elastic limit is raised, but the wire tends to be more brittle. For the reason already stated, however, the effect on ordinary round wire is not so great as on rolled wire or strip, and as a rule the effects of tinning are scarcely noticed. Occasionally in high tensile wire, such as piano wire, tinning affects the ductility tests adversely. On the other hand, possibly the increased elastic limit explains the preference for tinned wire among some makers of musical instruments.

The effect of hot galvanising is very much more important, because the wire is heated to a higher temperature. Pure zinc melts at 419° C., and, since it is necessary to allow a working margin above the melting-point in order to obtain a satisfactory coating on the wire, the temperature is seldom below 450° C., and is frequently as high as 500° C.—the average being about 470° C. The wire, however, scarcely reaches the temperature of the bath, because the period of immersion is generally less than fifteen seconds. It will be obvious, however, that the wire must superficially reach a temperature slightly above the melting-point of the zinc if a satisfactory coating is to be obtained, and, assuming that virgin spelter is used, it may be taken that the surface of the wire reaches at least 430° C. Before considering its effect on the physical properties of the wire it may be helpful to outline briefly the process itself.

Wire is galvanised by passing through a bath of molten zinc, the surplus zinc being removed by some wiping device as the wire emerges from the bath. Before galvanising, the wire must be thoroughly clean; sometimes it is pickled in the coil before being put on the swifts in front of the galvanising bath, but as a rule it simply passes through an acid bath before entering the galvanising tank. Some form of "flux" is also necessary, otherwise the metal will not "take" properly. Ammonium chloride or sal ammoniac is sometimes used on the surface of the zinc, at the entrance end, to act as a flux. "Killed spirits," or chloride of zinc—which may be obtained by adding zinc to the pickling bath—is also commonly used with or without the addition of sal ammoniac. If the wire has been previously cleaned in a separate

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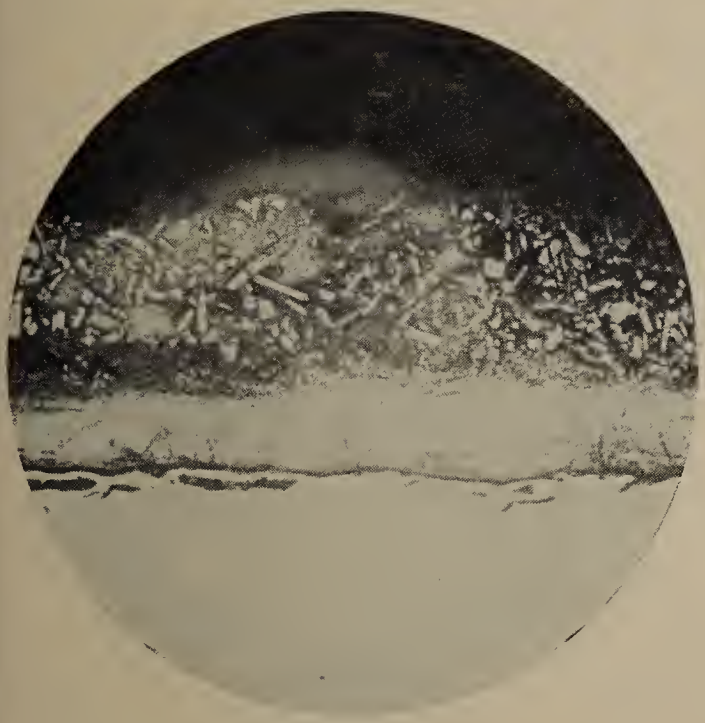

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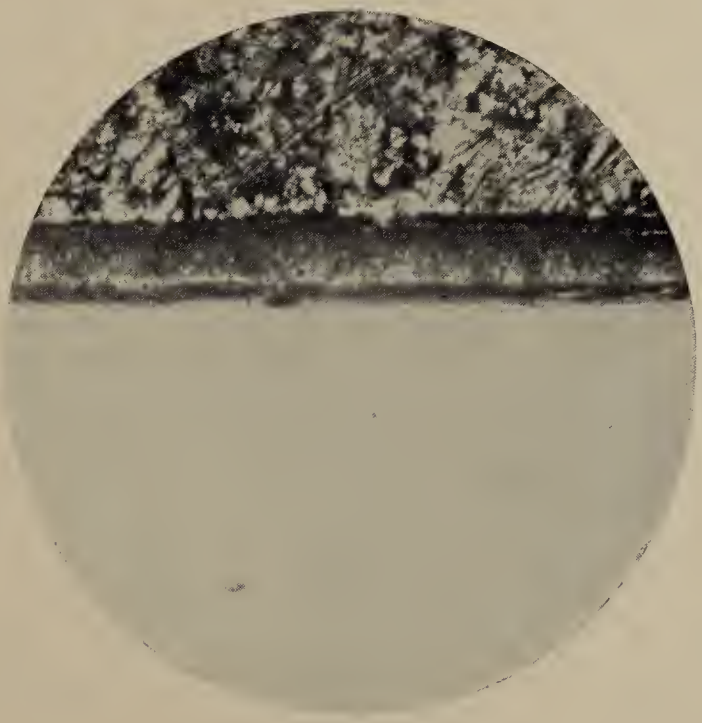

ZINC

WIRE

66

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Fig. 65. COATING OF ZINC-IRON ALLOYS ON A BADLY GALVANISED WIRE. N.B.—Two distinct Zinc-Iron Alloys are seen

Fig. 66. COATING OF ZINC ON A PROPERLY GALVANISED WIRE. N.B.—The upper portion of the Figure is simply a metal holder for the Section

Fig. 67. MARTENSITIC SKIN ON ROPE WIRE. Note the crack spreading from hard skin

tank, the tank in front of the galvanising bath may consist almost entirely of "killed spirits," with a very little free acid.

Zinc adheres firmly to iron or steel, because it forms a layer of iron-zinc alloy between the surface of the steel and the outer layer of spelter. If the zinc did not form this alloy the only practical process of coating wire with zinc would be electro-galvanising, since the processes of hot galvanising and sherardising depend on the existence of this alloy. It is not easy, for instance, to coat steel with lead by passing it through a lead bath in the same manner as galvanising, because lead forms no alloy with iron. The zinc-iron alloy is, however, extremely brittle, and if too thick a layer of it be formed, the coating will crack and peel off. If on the one hand the temperature of the galvanising bath be too high, and the surplus metal is wiped off the wire, on emerging from the bath the coating may consist entirely of this alloy (see Fig. 65). On the other hand, if the bath be too cold, a rough and lumpy coat of zinc will result, owing to the fact that large "dendritic" crystals of zinc have "set" on the surface before passing through the bath. The temperature of the bath must, in practice, be at least 30° above the melting-point of the spelter, and is generally a little higher—viz. about 470° C.—when virgin spelter is used. Assuming then that the conditions of temperature and time are arranged to get the best coat on the wire (see Fig. 66), we have to consider the effect of these conditions on the physical properties of the wire.

The deleterious effect of hot galvanising on high tensile wire is well known. If the temperature of the bath is high, the tenacity of the wire may be seriously reduced. Sometimes this does not matter, and the accompanying increase in elongation, it might be thought, would be sufficient compensation. The increase in elongation, however, after hot galvanising gives one rather a false impression of ductility, since reverse bending and torsion tests clearly show that galvanised wire is, from some points of view, more brittle than "black" wire. The results of tests carried out by the author are given in detail in Table 31, and for the sake of brevity these need be discussed in only a general way here.

TABLE 31

The Effect of Hot Galvanising on Wire

Three full pieces of wire with the following compositions were taken:

(1) *Mild Steel Wire*		(2) *Swedish* 0·60 *per cent. Carbon Steel Wire*		(3) *Swedish* 0·80 *per cent. Carbon Steel Wire*	
Carbon	0·12 per cent.	Carbon	0·59 per cent.	Carbon	0·81 per cent.
Silicon	0·04 ,,	Silicon	0·27 ,,	Silicon	0·19 ,,
Manganese	0·28 ,,	Manganese	0·38 ,,	Manganese	0·32 ,,
Sulphur	0·045 ,,	Sulphur	0·008 ,,	Sulphur	trace ,,
Phosphorus	0·031 ,,	Phosphorus	0·029 ,,	Phosphorus	0·033 ,,

A piece of each coil was galvanised at a temperature of 480° C. after receiving two, three, four, five and six holes respectively—*i.e.* five pieces of wire from each set of the following S.W.G.'s were available—8½, 10, 11½, 13 and 14½.

[*Table continued overleaf*

TABLE 31.—*cont.*

SET No. 1.—*Mild Steel Wire*

S.W.G.	*Diameter Inches*	*Maximum Stress Tons per square inch*	*Torsions on 100 Diameters*	*Bends 5 mm. Radius*	*Elongation per cent.*
Before Galvanising					
8½	0·152	35·43	74	6	6·25
10	0·127	40·88	35	6	6·25
11½	0·110	43·22	7	7	3·125
13	0·092	50·9	4	8	2·344
14½	0·075	52·4	5	9	2·344
Mean	..	**44·6**	**25**	**7**	**4**
After Galvanising					
8½	0·154	33·56	83	5	14·06
10	0·129	36·9	16	5½	10·94
11½	0·112	38·96	14	6	10·94
13	0·094	41·83	12	8	12·5
14½	0·077	44·12	12	10	12·5
Mean	..	**39·10**	**27**	**7**	**12**
Loss or gain %	..	12	8	0	200
SET No. 2.—*Swedish.* 0·60 *per cent. Carbon Steel Wire*					
Before Galvanising					
8½	0·152	78·72	40	4	5·5
10	0·128	83·97	40	5	4·7
11½	0·108	90·63	42	7	4·7
13	0·092	96·70	45	9	3·1
14½	0·077	99·72	43	11	3·1
Mean	..	**89·95**	**42**	**7**	**4·22**
After Galvanising					
8½	0·154	74·56	23	2	7·8
10	0·130	80·05	31	3	7·8
11½	0·111	82·56	31	4	7·8
13	0·095	86·26	30	5	7·8
14½	0·079	91·96	29	6	7·8
Mean	..	**83·08**	**29**	**4**	**7·8**
Loss or gain %	..	7·6	31	43	85

TABLE 31.—*cont.*

SET No. 3.—*Swedish.* 0·80 *per cent. Carbon Steel Wire*

S.W.G.	*Diameter Inches*	*Maximum Stress Tons per square inch*	*Torsions on 100 Diameters*	*Bends 5 mm. Radius*	*Elongation per cent.*
Before Galvanising					
8½	0·152	95·0	84	4	5·5
10	0·127	105·7	40	4	7·0
11½	0·108	111·0	43	6	6·25
13	0·091	120·0	40	7	6·25
14½	0·076	135·8	31	12	3·1
Mean	..	**113·5**	**38**	**7**	**5·6**
After Galvanising					
8½	0·154	88·7	13	2	7·8
10	0·130	94·2	11	2	6·25
11½	0·1105	101·5	18	4	6·25
13	0·094	106·0	15	4	6·25
14½	0·078	118·5	14	3	6·25
Mean	..	**102·0**	**14**	**3**	**6·56**
Loss or gain %	..	10	63	57	7·1

The most serious effect of hot galvanising, from the wire manufacturers' point of view, is the extraordinary reduction in the number of torsions which the wire will stand. Sometimes wire which appears to be perfectly satisfactory in the black state will, after galvanising, stand only one or two twists, indicating a serious lack of lateral cohesion. Reverse bend tests also show a serious increase in brittleness. Many different explanations of this have been offered, but none of them is fully satisfactory. The quality of the steel, overdrawing, faulty heat-treatment, and pickling are some of the causes suggested; but that these are only partial explanations is evident from the fact that even the finest qualities of wire suffer. The presence of the brittle zinc-iron alloy is also blamed for the failure in the torsion test. This, in all probability, contributes to the lateral weakness when it is present in excess, as is the case if the temperature of the galvanising bath has been too high. In extreme cases severe chemical action may take place, with serious attack on the ferrite areas, resulting in the production of a comparatively thick layer of an alloy containing as much as 6 per cent. iron, which may even penetrate the surface of the wire in little fissures: an obvious source of lateral weakness (see Fig. 65). This may indeed explain why galvanising at temperatures over 500° C. or prolonged immersion in the bath

produces brittle wire, even when it is softened considerably; but it does not explain why wire galvanised at temperatures as low as 430° C., where a thin layer only of the zinc-iron alloy, containing a much lower percentage of iron, is formed (Fig. 66), involving little or no surface attack on the wire, also fails in the torsion test, sometimes to an even greater extent than when high temperatures are employed. Moreover, the author has shown that an effect almost similar to that of hot galvanising is obtained by heating in a lead bath. The results of his experiments on this point also are given in Table 32. From these experiments, and from general

TABLE 32

Effect of Heating in a Zinc or Lead Bath

12-gauge wire of the following composition :

Carbon	0·73	per cent.
Silicon	0·15	,,
Manganese	0·67	,,
Sulphur	0·041	,,
Phosphorus	0·036	,,

No.	*Treatment*	*Diameter Inches*	*Maximum Stress Tons per square inch*	*Torsions on 100 Diameters*		*Bends on 3 Diameters*
					Mean	Mean
1	As drawn	0·107	125	23, 25, 25	24	11
2	30 seconds in zinc at 450° C.	0·107	110	5, 18, 14	12	..
3	15 minutes in zinc at 450° C.	0·107	92	8, 10, 12	10	..
4	1 minute in lead at 350° C.	0·107	123	20, 20	20	9
5	1 ,, ,, 400° C.	0·107	118	19, 18, 19	19	8½
6	1 ,, ,, 450° C.	0·107	110	22, 9, 14	15	7
7	1 ,, ,, 500° C.	0·107	96	21, 9, 11	14	6
8	1 ,, ,, 600° C.	0·107	74	32, 34	33	8½

experience, he has come to the conclusion that the effects of hot galvanising are due almost entirely to the influence of heat, and particularly the sudden application of heat to steel which has been cold worked; and this will depend on all the different points regarding the cold working of steel which have been discussed in this book. In short, hot galvanising or, in general, heating to temperatures in the neighbourhood of those employed in this process, constitutes the most sensitive test, not only of the steel itself, but of successful manipulation of it in heat-treatment and in drawing.

Even the finest steels and the finest wires are adversely affected by hot galvanising, and when there is any irregularity of composition or flow the effect is much more pronounced. This explains why the cause of brittleness in galvanised high tensile

wire is seldom traced to any obvious defect in the steel, since defects which pass unnoticed in drawing and in testing ordinary black wire, and effects of which are only revealed after galvanising, are naturally anything but obvious. Nothing, indeed, shows the need for high-class carbon steel in the wire industry so much as the behaviour of high tensile galvanised wire. The full effect of irregular flow is not felt until the wire has been galvanised, further proof of which is to be found in the fact, well known to wire galvanisers, that it is the thick wires which are most affected, fine wires being seldom seriously damaged. The reason for this lies in the fact that the finer the wire the more uniform is the plastic flow in drawing.

One other effect of hot galvanising, and of heat-treatment in general above 500° C., but below the critical temperature, remains to be mentioned—viz. the effect on the elastic limit and the fatigue point. It has already been shown that heat-treatment up to 400° C. increases the elastic limit, and in all probability the fatigue limit of wire; and although there is a slight decrease above 400° C., the galvanising range of temperature is still sufficiently low to ensure that these limits will at least not be lower than in the black wire. As a matter of fact, galvanised wire has generally a higher elastic limit than freshly drawn wire; but if the temperature of the galvanising bath has been excessive, or prolonged immersion in the spelter has taken place, mild steel wire may be annealed and high carbon wire partially annealed with a consequent lowering of both the elastic and the fatigue limits. In galvanised high tensile wires the initial stages of the divorce of pearlite or sorbite may be seen in a microsection, and if this is carried too far the elastic and fatigue resisting properties may suffer. As a rule, however, the temperature is not sufficiently high for this annealing effect to take place.

The conclusions regarding the conditions to be aimed at in hot galvanising of high tensile wire which the author reached, as a result of his experiments, were as follows:

"The temperature of the galvanising bath should be as low as possible, and the wire should be immersed in the bath for as short a period as possible, consistent with the production of a satisfactory coating of zinc"; and it might be added that, wherever possible, other methods of applying a coating of zinc to high tensile wire should be adopted. Such processes as "sherardising," "electro-galvanising" and "bruntonising" may be mentioned; but, since they lie outside the scope of this work, need not be described here.

CHAPTER VIII

TYPICAL APPLICATIONS OF WIRE

To discuss in a single chapter the properties of wire for all, or even a few, of the many purposes to which it is applied, is obviously impossible. Fortunately, such a complete consideration of the subject is quite unnecessary. For this purpose wire can be conveniently grouped, and the properties of one example from each group may be taken as typical.

Group one comprises mild steel wire only, which has a useful range of from 25 to 70 tons per square inch tensile strength, according to diameter.

In the soft annealed condition it has many useful applications. In the lightly drawn condition it has all the peculiar virtues of toughness implied in the typical stress-strain diagram, Fig. 48, and in the SN curve, Fig. 58 (curve 2), which indicates great endurance under repeated overstressing. In the hard-drawn condition it should be used with discretion. At this stage it overlaps mild patented steel wire, which is generally a safer and more reliable material.

Since the main object of the patenting process is to produce sorbite, it cannot usefully be applied to wire with a carbon content below 0·30 per cent., and except in thick sizes the tensile strength of patented wire is seldom below 60 tons per square inch. Between this and 100 tons per square inch lies the range of the milder varieties of patented steel wire, and the chief virtue of this class may best be summed up in the term toughness—*i.e.* strength and ductility. Sometimes it is difficult to decide whether a hard-drawn mild steel or a lightly drawn patented steel wire should be used for a particular purpose.

The problem here is not entirely a technical one, but is often complicated or decided by commercial considerations, the mild steel being cheaper.

A good example of a doubtful case is provided by railway-signal wire, used either in the form of rope strand or as a single wire.

While tensile strength is desirable it must not be obtained at the expense of other essential properties. The wire must be sufficiently ductile to stand bending round small pulleys—*i.e.* it must have considerable power of endurance under repeated stresses far in excess of the limiting fatigue stress, and the wire most suited to withstand these is a lightly drawn mild steel as curve 2 in Fig. 58 demonstrates. On the other hand, it must not stretch too much, and so the elongation of the wire must be restricted. It must have a good tensile impact value since it receives many suddenly applied loads. So long as the tensile strength required does not exceed 50 tons per square inch, mild steel wire generally gives satisfaction, but there is a demand for tenacities up to 70 or more tons per square inch in this wire, and mild

steel of this strength is often rather brittle, and in such cases patented steel wire would seem to be more satisfactory.

One of the most important applications of cold-drawn mild steel is in the form of bright-drawn bars for shafting, automatic machines, case-hardening, and shape wire, etc. The properties of such material have been very fully investigated by Brown.[1] One defect of such material is the uncertainty of the Izod value in cold-worked mild steel. Some figures illustrating this are given in Table 16.

The second group includes all wire which is drawn for size and shape only, and where the physical properties in the drawn condition are of very minor importance, the only requirement being sufficient softness to permit of machining or wire forming. Such wire falls under the general term of Silver Steel, and its treatment has already been fully described in Chapter IV.

The third, and perhaps most important group, is typified by rope wire and spring wire. These two types do not differ very greatly, and there is certainly no definite line of demarcation between them. A good rope wire, for instance, is often the best wire for certain types of spring, and a good spring wire is sometimes the best wire for some ropes. But in general there are sufficient differences in properties and methods of manufacture between one and the other to necessitate a separate consideration of each.

SPRING WIRE

Wire springs are, of course, made from almost every conceivable variety of wire, and our first two groups also include spring wire, but spring wire of the high tensile variety is made from hard-drawn patented steel wire in various grades, according to quality, size, tensile strength, and physical properties in general.

Most spring wire of this class is made from the finest qualities of carbon steels available.

In general the properties sought in high-grade spring wire are high elastic limit, more especially torsional elastic limit and high values for the limiting fatigue stress. Fortunately, the treatment necessary to obtain the optimum values in these properties is in general identical, and has already been indicated in Chapter VI.

There are some springs, however, where great toughness is essential and even more important than the above-mentioned properties—*e.g.* cycle saddle wire, and such wire more closely resembles rope wire.

Probably no finer grade of spring wire is made than that designed for the valve springs of an aero engine. In this country such wire is covered by two Air Ministry specifications "D.T.D.4.A" and "D.T.D.5.A." In the former the wire is a chrome vanadium steel and falls into the second group of wires discussed in this chapter because the wire itself is supplied in the soft annealed condition, the springs being subsequently hardened and tempered. In the latter the wire is a carbon steel wire with the limits for carbon content restricted at present to 0·70 to 0·80 per cent.,

and the tensile strength after blueing at a maximum temperature of 375° C. to a minimum of 95 and a maximum of 120 tons per square inch.

While it is possible that further research work may suggest modifications in this specification, its present purpose is intended to provide wire with the desired properties—viz. high elastic limit and high fatigue limit combined with a reasonable degree of toughness to be ensured by the reverse bend test also specified. Two other important points are specified: a surface finish in the wire showing freedom from all visible defects such as die marks, and freedom from decarburisation to be ensured by grinding the rod at some stage in the course of manufacture.

Which of these two types of spring wire is the more satisfactory for the purpose is a point about which there is not unnaturally some difference of opinion. From the point of view of toughness the patented and drawn wire is generally considered the more reliable, and from research work at present under way into the effect of carbon content, cold drawing, and low-temperature heat-treatment on the limiting fatigue stress, it seems probable that the drawn wire will ultimately prove the more satisfactory material in every respect.

ROPE WIRE

Obviously the properties required in rope wire can best be determined from an inquiry into the working conditions of the ropes themselves, and particularly into the causes of failure. The results of such inquiries have been recorded by Desch,[2] the Safety in Mines Research Board,[3] and Woernle and his co-workers in Germany, and many others.

In selecting and specifying a wire rope for a certain purpose the tensile strength is nearly always the first point considered. In many cases the breaking load, the size, and possibly the construction are the only things specified, the rest being left to the rope manufacturer. This is natural, since the one thing the user must know is the load the rope is capable of carrying. Yet cases of ropes breaking under static loads are extremely rare, and when they do occur gross carelessness and neglect are almost certainly evident. Only one such case has come under the author's notice—viz. the failure of a derrick guy rope during the lifting of light loads from a ship's hold. The guy rope in question consisted mainly of iron oxide.

Under dynamic loading failures are more common, but even so they rarely occur until the ropes have deteriorated in service. It is because of the uncertainty regarding the stress due to dynamic loading and the damage due to corrosion, wear, and repeated stressing, etc., that factors of safety are extremely high; so high indeed that they are better described as factors of ignorance.

From theoretical calculations Vaughan estimated that, discounting serious accidental overloads, the greatest load which a winding rope was likely to receive was three times the static load. This calculation has since been virtually confirmed experimentally by the Safety in Mines Wire Ropes Research Committee.[4]

The stresses to which the individual wires in a rope are submitted are extremely

complex. The rope as a whole is subjected to tensile and bending stresses, but a wire rope is a structure and does not behave like a solid bar or even like a collection of parallel wires. The wires are laid up in the rope in the form of helical springs, but these are not completely free to operate as such, and their behaviour varies according to the friction between wires. Thus the stresses imposed on the wires depend on many factors, such as the construction of the rope, the lay of the rope, and the internal condition—*i.e.* whether the rope is well lubricated or dry. There is, however, one striking difference between a new and an old rope—viz. that the modulus of elasticity of an old rope is nearly double that of a new one. This was pointed out many years ago by Goodman in his excellent text-book on "Applied Mechanics," but no one seems to have appreciated its significance. This was impressed on the author during a visit to a colliery, when he saw an old haulage rope being spliced after a break. The splicer remarked that it was a waste of time splicing the rope since it would very soon break again. Now the splicer had certainly never heard of the Young's modulus, and would not have been impressed if he had, but he knew the rope had "no life in it"—his expression was much stronger than this.

The main reason why the old rope breaks under sudden overload, which would have little effect on the new rope, is that the latter can yield and stretch and so dissipate the load. Of course there are other reasons: the wires are corroded, worn, and fatigued. Even so, the actual breaking load is possibly not far short of the original breaking load, and it is really because the old rope cannot stretch that it fails suddenly.

It has been suggested that the factor of safety should be based on the fatigue limit of the wire rather than on the breaking load of the rope. If the conditions of service could be controlled so that fatigue would be eliminated this would be sound practice, but in most cases this is quite impossible. All experience shows that at present fatigue is inevitable and must be regarded as one of the factors in wire deterioration, like corrosion and wear, etc. Under these conditions it would be just as logical to base the factor of safety on the resistance of the wire to corrosion. The true factor of safety must be the relationship between the actual breaking load of the rope at any particular moment and the greatest load it is asked to stand.

The breakage of an endless haulage rope is, of course, not generally so serious a matter as that of a crane or winding rope. Winding ropes especially simply must not be permitted to break, and they are rightly removed from service long before there is any appreciable danger of complete failure. It is therefore clear that in practice rope failures are due to the damage received in service, and the problem for the manufacturer of rope wire is what kind of wire is best suited to withstand this damage.

Corrosion.—One of the most important factors influencing the life of wire ropes is corrosion. This is most serious in ropes used for marine purposes, and nearly all such ropes are made with galvanised wire. It is not always fully realised, however, that galvanised wire is not rustless but merely rust-resisting. Builders who use galvanised steel for roofing, etc., know this perfectly well, and generally apply

paint as an additional protection against corrosion. It is not always practicable to apply paint to wire ropes, but in many cases where they are used only as structural members, *e.g.* in ships' rigging, painting is quite feasible. In other cases additional protection can be obtained by frequent applications of grease. Grease can be supplied internally as well as externally in many cases by the inclusion of well-greased hemp fibres in the strands, as well as in the main cores. Fibres well impregnated with rope grease can be spun into the strands along with the steel wires, and are extremely useful in supplementing the protection afforded by galvanising.

In special cases, where cost is not of primary importance, stainless steel and monel metal ropes can, of course, be used.

The protection of ropes for mining and other purposes, where the rope has to run over pulleys, is a more difficult problem. One is inclined on first thoughts to rule out the use of protective coatings in this case since such coatings are quickly worn away. It should be remembered, however, that internal is often a more serious problem than external corrosion in such ropes, and that so long as some zinc remains in the interstices of the rope there is a powerful protecting influence. Moreover, zinc is an excellent lubricant and the use of zinc-coated wire for mining and other purposes could be greatly extended with advantage. But zinc as a protective coating has one great drawback; it will not resist acid, and, where in many instances the water in mines contain appreciable quantities of acid, other methods of retarding corrosion have to be employed.

In all cases, whether the wire is zinc-coated or not, ropes should be thoroughly impregnated with grease. Most ropes are treated with lubricating and protective greases during manufacture, and every effort should be made to retain this lubrication during service. The importance of efficient lubrication cannot be too strongly emphasised. Recently it has been shown by Goodacre [5] that wires which are covered with certain lubricants actually acquire an increased resistance to fatigue. It is naturally difficult, and often impossible, to get oil or grease into a rope once it is made, especially when the rope is under load, but this is unnecessary provided grease is applied externally frequently enough to prevent the original internal lubricant escaping.

Efforts have been made from time to time to retard corrosion by the use of copper-bearing steels, and although little data is yet available regarding the results obtained, it seems that some improvement along this line is probable.

Finally, it should be noted that in general high tensile wire is more subject to corrosion than low tensile wire.

WEAR AND FRICTION

Efforts to increase the resistance to wear in wire ropes introduce new problems and often defeat their own object. The effects of wear may be considered from two points of view: (1) the reduction in metallic area involved; (2) the local cold working and consequent hardening of the wire. Wear occurs on the crowns of the

strands, quickly reducing them to a point where a larger metallic surface is exposed, when wear becomes more general. At first sight it may seem that the harder the wire is the better it will withstand wear. A hard wire will certainly be less easily reduced in metallic area, but it will be more readily damaged by the cold work involved in wear, particularly when wear is accompanied by bruising and crushing.

Some interesting research work into the effects of abrasion on rope wire was begun by Goodacre, and although the work was not carried to a conclusion, the results obtained indicated that the behaviour of wire under abrasion was by no means a simple matter depending merely on the relative hardness. It was shown that wear was greatly influenced by oxidation—a fact which has been confirmed by some German investigators, one of whom found that the removal of metal by abrasion could be prevented entirely in the absence of any oxidising influence. It is clear, therefore, that the problems associated with abrasion and wear are extremely complex in their practical aspect as applied to rope wire, and the field for research here is a wide one.

It is not easy to say when a wire has fractured to what extent this fracture is due to wear or repeated bending stresses, etc., but wire breakages are sometimes initiated by skin hardening of already hard wire through friction. Two cases of failure which were definitely traced to this cause may be given here by way of illustration.

The first is a case of a winding rope of the flattened strand type—a type designed specifically to increase the resistance to wear and, therefore, a good illustration of the author's point that efforts to reduce damage by wear sometimes defeat themselves. The wire in this rope had an average tensile strength of 112 tons per square inch and a carbon content of 0·70 per cent. Failure was due to excessive skin-hardening, resulting in the development of surface cracks. The friction which caused the skin-hardening was ultimately traced to a fault in the winding conditions, but the absence of appreciable reduction in the cross-sections of the wires by wear allowed that fault to go unsuspected until it was diagnosed in a post-mortem examination of the rope. This failure through hardening by excessive cold work of the wire skin would not have occurred but for two factors, both calculated to resist wear: (1) the flattened strand construction; (2) the hardness of the wire. Had the rope been made of wire of softer, or of more ductile quality, it is probable that the signs of wear would have been more obvious, and the trouble cured before any wire breakages occurred.

The above remarks are not intended to imply that the use of high tensile wire is always objectionable, still less that the flattened strand construction is so, but to demonstrate the necessity of caution in dealing with the difficult problem of resistance to wear. In general it is safer that a wire should wear without cracking than that it should resist wear, and in doing so initiate fracture. Though, of course, to go to the other extreme and use a really soft wire which would wear away very quickly would be absurd, especially when the size and construction of the rope necessitated the use of very fine wires.

The second case is one of wire fractures initiated by the development of a martensitic skin through friction. The possibility of this has been mentioned by Atkins and Primrose, but these investigators did not apparently consider the phenomenon sufficiently rare or surprising to necessitate any special comment. It may be thought that this is an extremely rare occurrence; it is in fact quite common in traction and logging ropes, and is occasionally found in haulage ropes. Obviously the presence of martensite on the worn edge of a rope wire, as illustrated in Fig. 67, cannot be accounted for by work hardening, since martensite can be formed directly from austenite only, and one must conclude, therefore, that the surface of the wire was heated by friction above the critical temperature. In order to prove this possibility a piece of wire of sufficiently high carbon content was held tightly in contact with a revolving hardened steel pulley until it was considered that sufficient frictional heat had been developed. The heated wire was then quenched by water. At first the results were somewhat uncertain owing to the difficulty of judging the portion of the wire where the greatest heat was developed, but the obvious remedy of carrying out the experiment in the dark soon supplied the required proof. Not only was the skin of the wire heated to redness but at one point the whole cross-section of the wire. This portion when quenched by water was naturally martensitic throughout. As a matter of interest it may be mentioned that this position occurred at the point where the wire first made contact with the pulley—*i.e.* about 10 o'clock, with the pulley revolving clockwise. This fact, no doubt, could have been predicted from theoretical considerations.

Returning now to the general consideration of the service conditions of rope wire, other factors to be considered are bending stresses and direct loading. Many attempts have been made to calculate the bending stresses to which the wire in a rope are subjected, but no very definite conclusions have been reached. It is probable, however, that when pulleys and drums are made sufficiently large the purely bending effect is not so serious a factor in wire failure as is generally supposed. When the load on the rope is great, the additional tension due to bending may certainly be quite sufficient to cause severe straining of individual wires, but failure due to bending stresses is probably more common in ropes such as oil-well ropes where pulley diameters are small. The most serious damage caused by bending round pulleys is due rather to friction, wear, and the crushing effect of one wire against another or against the grooves of the pulleys. Another effect of severe bending is the displacement of strands and wires which disturbs the uniform distribution of the load. As with wear, it is essential that the wires, whether of high tensile or low tensile grade, should be capable of withstanding deformation without splitting or becoming brittle.

Direct Loading.—Seldom, if ever, is failure due to direct static loads. The overloading which damages or breaks a rope is probably always dynamic, and it is because provision has to be made for the uncertainty regarding this that a high factor of safety is demanded, particularly for winding ropes.

Up to a certain point the behaviour of a rope is analogous to that of a spring,

and when the rope is new it behaves as a spring which receives frequent but intermittent overloads. A spring is designed so that the greatest load it has to stand will not cause any appreciable permanent distortion. In addition, if the spring is to be subjected to constantly repeated stresses it must be able to stand these indefinitely; in other words, the greatest load applied must be within the limiting safe range of stress. A good example of this type is the aero engine valve spring. In some springs the heavy loads are applied so infrequently that so long as they do not cause appreciable permanent deformation they may occasionally exceed the safe range without causing breakdown. An example of such a spring is that of a cycle saddle.

In the great majority of wire ropes the conditions are such that the wires are frequently stressed beyond the safe range. In haulage ropes in particular this is so, to such an extent that the helical strands as a whole are permanently distorted—that is, the lay of the rope is lengthened. The general effect of all this overloading, whether caused by direct kinetic loads, bending stresses, crushing, bruising, friction, or wear, is to cause a gradual destruction of the wire. This slow destruction, although largely the result of repeated stresses, is clearly something quite different from what is ordinarily understood by fatigue. It is the result of stresses much greater than those which cause failure only after several millions of applications. With stresses in the neighbourhood of the fatigue limit there is little or no deformation: with those which cause the destruction of rope wire there is severe straining.

In most of the published work on the fatigue of metals, the determination of the actual fatigue limit or limiting safe range of stress has been regarded as the important object of the experiments. Little attention has been paid to the period of endurance of the specimen under stresses well above the fatigue limit. It has, indeed, been expressly stated by some investigators that it is a matter of little importance whether a specimen stands ten thousand or several hundred thousand stress repetitions so long as it is subjected to a load which will eventually cause failure. In so far as the slope of endurance curves has been considered at all it has generally been thought a disquieting feature when it shows a persistent downward tendency, as in some of the non-ferrous metals, even after several million cycles of stress.

No doubt from a purely theoretical point of view this insistence on the supreme importance of a definite fatigue limit is entirely sound. In practice, however, there are undoubtedly many cases where a metal component is subjected in the course of its normal life to stress repetitions of the order of tens or hundreds of thousands only, and where the stresses must at times be of considerable magnitude—that is, well beyond the safe range.

Any consideration of the material to be used in the construction of wire rope, therefore, must begin with the question, "Is over-stressing of the wire inevitable or not?" To a certain extent it obviously is inevitable. Wear, friction, crushing, etc., are certain to occur, but one may legitimately suppose that in a rope properly constructed of suitable material and of the correct size, strength, and flexibility

for a particular purpose, the limiting safe range of stress need not be exceeded. If this be so, then it would seem that wire with a high fatigue limit would be the most desirable, especially if this could be secured in a wire which at the same time possessed considerable ductility.

An experiment designed to investigate this is described by the author [6] elsewhere, followed by a discussion on the relative importance of the fatigue limit of rope wire, but since the question of fatigue has already been discussed in Chapter VI., it will be sufficient here to summarise briefly. While admitting the value of a high fatigue limit in rope wire as in any other material which is subject to repeated stresses it is argued in the above-mentioned paper that other properties, apparently inconsistent with a high fatigue limit, are more important. These properties may perhaps best be summed up by the term toughness, and in them is involved the power of endurance of material under repeated stresses above the fatigue limit. It is emphasised that wire ropes have in general a limited life and that the endurance required in most cases does not involve resistance to millions of stress cycles but rather to 50,000 or 100,000. Naturally, this view of the matter has been challenged and has by no means met with general acceptance. Obviously it does not apply in any case to all wire ropes.

In a publication by Pomp and his co-workers the comparative values of tensile reverse bending, torsion, and fatigue tests in rope wires in co-relation with rope endurance tests are discussed, and from the conclusions which the present author reached from a study of this work it would appear that his views are fully confirmed therein.

The whole question of rope wire is so involved that some recapitulation is required here by way of summing up the position. So many factors enter into the manufacture of wire, and so wide are the permissible variants in the operations involved, that it is impossible to lay down any hard and fast rules governing either the methods of manufacture, or the tests which the wire must stand. Only by a careful consideration of existing data and the almost intangible evidence which guides the practical man can some approach to the problem be made. To enumerate the more important factors which influence the quality of a wire:

(1) The quality of the steel is probably the most important.
(2) Its composition in relation to its purpose.
(3) Its heat-treatment, which may be subdivided as follows: (*a*) temperature reached; (*b*) time of heating; (*c*) rate of cooling.
(4) Descaling or pickling operations.
(5) Drawing operations, which include the following:
    (*a*) Total reduction from rod.
    (*b*) Total reduction after final patenting.
    (*c*) Stages of reduction or of programme of draughting.
    (*d*) Method of drawing—*i.e.* single holing or continuous, speed, wet or dry.

In addition to these factors influencing the wire itself, the problem is further complicated by the fact that the properties required in the rope wire are not definitely known or defined with accuracy, nor is it known with sufficient certainty how such properties as are known to be desirable can be measured by means of tests on the wire. Further difficulties are the varieties of rope construction and the conditions of service. Thus a wire which may have been found suitable for one rope of a certain construction may be quite unsuitable for another differently constructed, or in two identical ropes wire which is suitable in one may be unsuitable in the other because the service conditions are totally different.

When the problems are thus stated they appear well nigh insoluble, and so possibly they are in their entirety.

Fortunately practical experience, which is always well ahead of exact scientific knowledge, or "absolute experience," enables us to use wire ropes daily with comparative safety. "When it is possible to relate the manufacturing operations to absolute experience," as Robertson puts it, "all differences of method and opinion will vanish, all heat-treated rod will be in perfect conformity with the drawing operation, all finished wire will possess the exact properties required, and all wire ropes will behave in accordance with prediction—there will be no rejections and no failures." In the absence of "absolute experience" no dogmatic conclusions regarding the treatment and properties of rope wire are given here, but some idea of the present state of our knowledge of the subject may be formed from points summarised below.

Tenacity.—While high tensile strength is desirable in most cases, and essential in many, its attainment involves some sacrifice of other important properties, and if due precautions are not taken the objects aimed at may be defeated. In this connection regard must be paid to the following points: the maximum tensile strengths permissible depend, among other things, on the diameter of the wire, the quality of the steel, and the particular application of the rope. A wire of 0·021 inch diameter with a tenacity of 120 tons per square inch is a very different thing from one of 0·128 inch diameter of the same relative strength. The former can be obtained without overdrawing from a steel containing only 0·40 per cent. carbon, while the latter requires, with the same amount of drawing, a carbon content of about 0·80 per cent. Further, in the thicker wire, the use of special acid steel is almost essential if a wire of satisfactory quality is to be produced, while basic steel will generally be satisfactory for the thinner wire.

For standing rigging ropes and the like much higher strengths can be reached with safety, and the tensile strength of such wire varies from 100 to 150 tons per square inch, according to wire diameter and the requirements of the rope.

In every wire there is a maximum tensile strength which may be reached without appreciable sacrifice of other essential properties. Since the degree to which these other properties are essential varies, the permissible maximum tensile strength varies. In most running ropes, however, it may be taken that tenacities from 110 to 120 tons per square inch are seldom exceeded with advantage, and in many cases

such wire is used where wire of lower strength would give better results, particularly in the thicker sizes.

The point of maximum efficiency—*i.e.* the optimum point in drawing at which the best possible combination of desirable properties is attained—has not yet been determined, but certain endurance tests which have been carried out indicate that with high-grade wires round about 0·052 inch to 0·021 inch diameter there is a slight but definite increase in efficiency up to a strength of about 110 tons per square inch. It has been found, however, that the endurance of ropes with wire of these sizes between 100 and 110 tons tenacity is not more than from 10 to 15 per cent. greater than that of similar ropes with wire of 80 to 90 tons tensile strength tested under identical conditions, and that with wire of 130 to 140 tons tenacity the endurance is less than with 80 to 90 ton wire. It is thus becoming increasingly clearer that the deductions from practical experience are right in regarding 120 tons per square inch as approximately the maximum tenacity permissible in wire for running ropes. If this be so for thin wires it suggests that lower tenacities are desirable with thicker wires, probably 100 to 110 tons per square inch.

The tendency to specify the higher tensile grades of wire for all purposes has increased alarmingly of late, and cases of ropes made with wire of 110 to 120 tons tensile strength used when the factor of safety is as high as 20 are not uncommon. Sometimes this is justified, for example when the wires are so thin that resistance to wear must be almost complete; but with thick wires, where high tensile strength involves the use of high carbon steel, increased advantage through resistance to wear is doubtful and efficiency is lost. While high tensile wire increases the breaking load of the newly made rope, it is the tenacity of the rope after several months' service that is the vital point. The author believes this tendency has gone too far, and certainly there is far more trouble through wire breakages in ropes with wire over 100 tons tensile strength than in those with lower tensile wire. High tensile wire should be used with great discretion, and, when conditions permit, the use of the lower tensile grades should be preferred. Finally, in this connection it should be remembered that the use of high tensile wire involves not only a sacrifice of the properties of ductility, toughness, and endurance, but as the results of the solubility tests recorded in Chapter VI. show a decreased resistance to corrosion.

ALLOY STEEL WIRE

A final word may be added regarding the applications of alloy steel wire. For the most part these fall into the second group mentioned in this chapter, where the material is drawn into wire not because its properties in the cold-drawn condition are of interest, but because it is desired in the form of a metallic thread. In such cases the only question of importance is how to reduce these refractory alloys in the easiest possible way. With such alloys as high-speed steel the treatment is somewhat similar to that employed with high-carbon steel, and the annealing operations have to be carried out so as to get the carbon in the steel into the spheroidal

form, and the annealing temperature is generally between 700° C. and 800° C. Even after the most thorough annealing it is seldom possible to draw such wire more than 1 light pass.

Nickel and nickel-chrome steels for subsequent heat-treatment, although easier to draw, are usually annealed between each pass, though the reduction per pass may be heavier. Stainless steels of the original Brearley variety and higher chromium type covered by B.S.I. Specification S.80 also fall into this group, but the austenitic stainless steels belong to our third group since they are hardened by cold working only.

The use of this material in the form of hard-drawn wire for such products as springs and ropes is increasing greatly. It can be produced with tenacities up to 150 tons per square inch in the fine sizes of wire, and although, as yet, its ductility and toughness in the hard-drawn condition does not equal that of carbon steel wire, torsion values varying from 20 to 40 in 100 diameters can be obtained. As in the case of carbon steel the higher torsion values are obtained only when the reduction by drawing exceeds a certain percentage.

Austenitic steels are extremely ductile in the fully softened condition, but they harden up rapidly with drawing owing to the transition to martensite produced by cold work.

It is possible that some modification in composition of these steels, or in the cold-drawing methods, may result in the production of a tougher variety of the wire, in which case its use may be greatly extended.

One other alloy which may find useful application in the form of wire is the new K Monel.

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APPENDIX

PRINCIPAL WIRE GAUGES IN APPROXIMATE DECIMALS OF AN INCH

ALL other gauges are now more or less obsolete except those used for music wire. On the Continent most wire is now designated by the diameter in millimetres.

Abbreviation :	S.W.G.	Stl. W.G.	A.W.G.	B.W.G.
No. of Wire Gauge	*British Standard Wire Gauge*	*American Steel Wire Gauge*	*American Non-Ferrous or Brown and Sharpe*	*Birmingham Wire Gauge*
0000000	0·5000	0·4900	..	..
000000	0·4640	0·4615	0·5000	..
00000	0·4320	0·4305	0·5165	0·500
0000	0·4000	0·3938	0·4600	0·454
000	0·3720	0·3625	0·4096	0·425
00	0·3480	0·3310	0·3648	0·380
0	0·3240	0·2065	0·3249	0·340
1	0·3000	0·1830	0·2893	0·300
2	0·2760	0·2625	0·2576	0·284
3	0·2520	0·2437	0·2294	0·259
4	0·2320	0·2253	0·2043	0·238
5	0·2120	0·2070	0·1819	0·220
6	0·1920	0·1920	0·1620	0·203
7	0·1760	0·1770	0·1443	0·180
8	0·1600	0·1620	0·1285	0·165
9	0·1440	0·1648	0·1144	0·148
10	0·1280	0·1350	0·1019	0·134
11	0·1160	0·1205	0·0907	0·120
12	0·1040	0·1055	0·0808	0·109
13	0·0920	0·0915	0·072	0·095
14	0·0800	0·0800	0·0641	0·083
15	0·0720	0·0720	0·0571	0·072
16	0·0640	0·0625	0·0508	0·065
17	0·0560	0·0540	0·0453	0·058
18	0·0480	0·0475	0·0403	0·049

PRINCIPAL WIRE GAUGES IN APPROXIMATE DECIMALS OF AN INCH—*cont.*

No. of Wire Gauge	*British Standard Wire Gauge*	*American Steel Wire Gauge*	*American Non-Ferrous or Brown and Sharpe*	*Birmingham Wire Gauge*
19	0·0400	0·0410	0·0359	0·042
20	0·0360	0·0348	0·0320	0·035
21	0·0320	0·0317	0·0285	0·032
22	0·0280	0·0286	0·0253	0·028
23	0·0240	0·0258	0·0226	0·025
24	0·0220	0·0230	0·0201	0·022
25	0·0200	0·0204	0·0179	0·020
26	0·0180	0·0181	0·0159	0·018
27	0·0164	0·0173	0·0142	0·016
28	0·0148	0·0162	0·0126	0·014
29	0·0136	0·0150	0·0113	0·013
30	0·0124	0·0140	0·0100	0·012
31	0·0116	0·0132	0·0089	0·010
32	0·0108	0·0128	0·0080	0·009
33	0·0100	0·0118	0·0071	0·008
34	0·0092	0·0104	0·0063	0·007
35	0·0084	0·0095	0·0056	0·005
36	0·0076	0·0090	0·0050	0·004
37	0·0068	0·0085	0·0045	..
38	0·0060	0·0080	0·0040	..
39	0·0052	0·0075	0·0035	..
40	0·0048	0·0070	0·0031	..
41	0·0044	0·0066	0·0028	..
42	0·0040	0·0062	0·0025	..
43	0·1036	0·0060	0·0022	..
44	0·0032	0·0058	0·0020	..
45	0·0028	0·0055	0·00176	..
46	0·0024	0·0052	0·00157	..
47	0·0020	0·0050	0·00140	..
48	0·0016	0·0048	0·00124	..
49	0·0012	0·0046	0·00099	..
50	0·0010	0·0044	0·00088	..

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